



## **Status of the POLARIS laser system**

Marco Hornung

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**HECDPSSL, Lake Tahoe 11-14. September 2012**

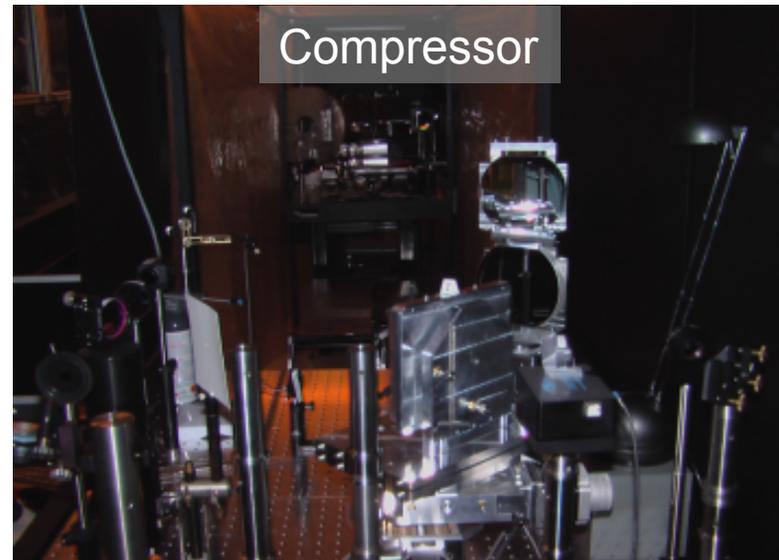


## Petawatt Optical Laser Amplifier for Radiation Intensive Experiments

**In the beginning of 2012: Milestone of first successful experimental campaign**

$\lambda_c = 1030 \text{ nm}$   
Pulse Energy = 6.5 J (4J on target)  
1 shot every 40s  
Pulse Duration = 160 fs  
Peak Intensity =  $5 \times 10^{20} \text{ W/cm}^2$   
Temporal Contrast =  $10^{-9}$

# 2005: 2<sup>nd</sup> HECDPSSL - Jena



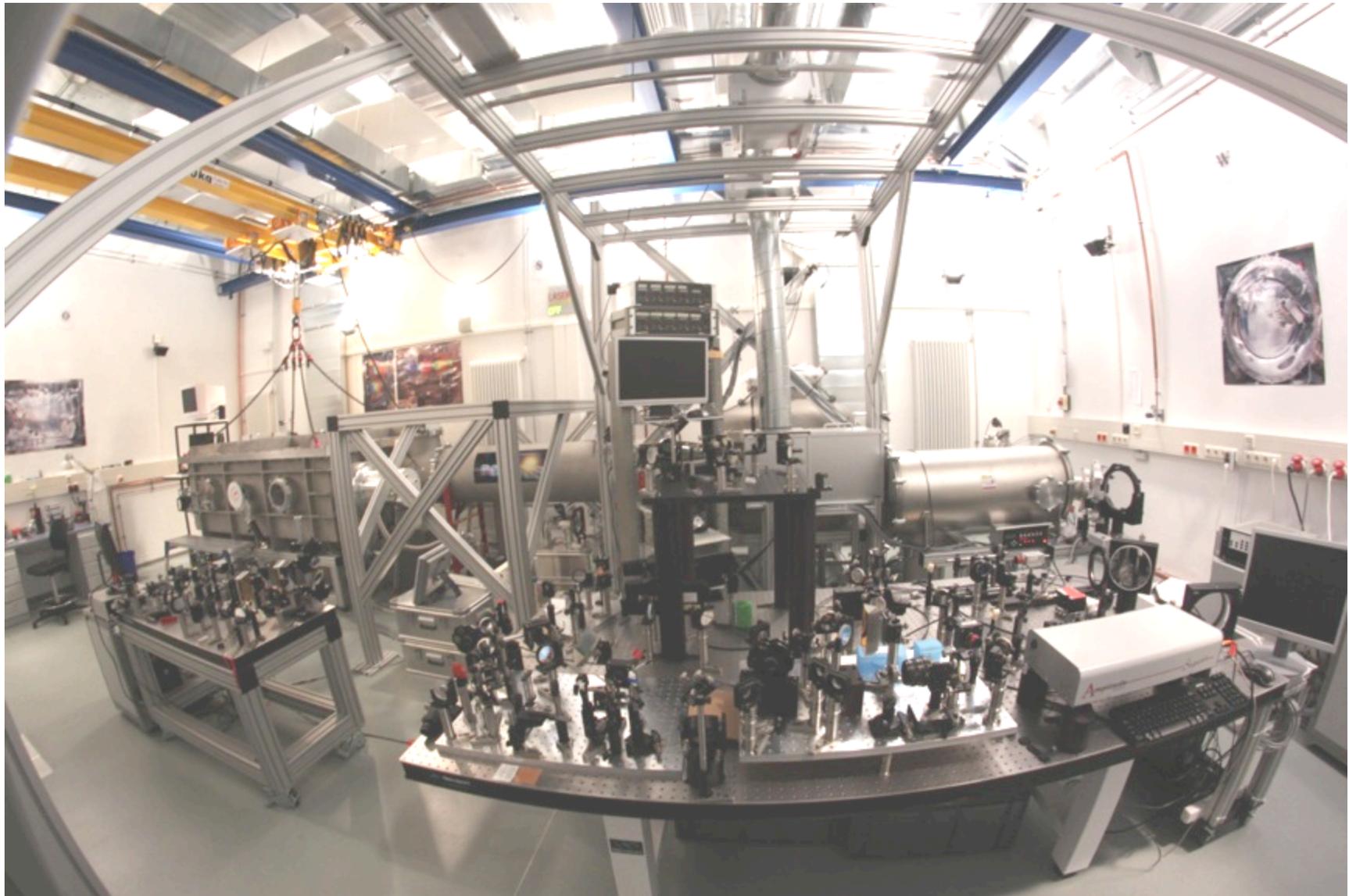
# Lab1: Front End & Amplifier A1-A4



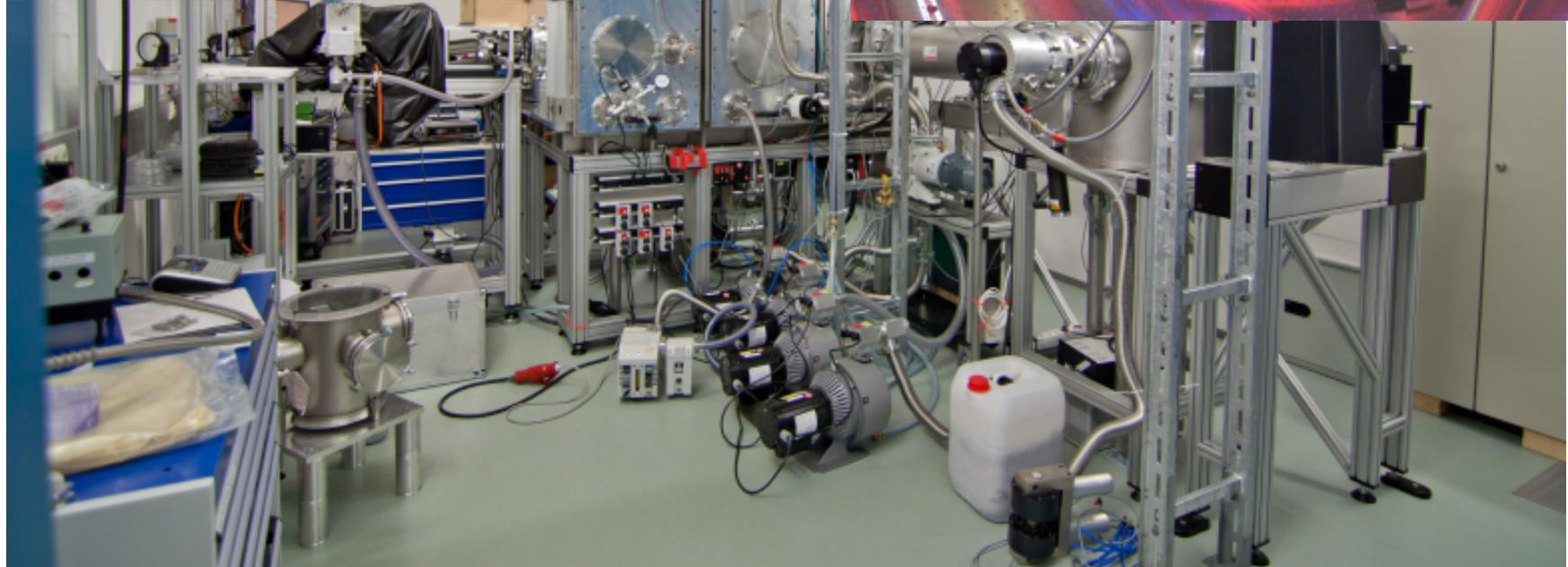
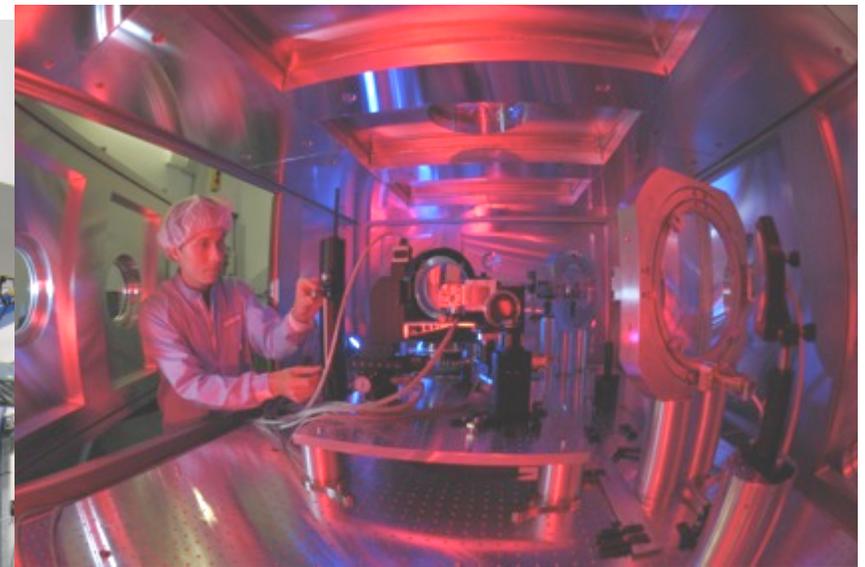
# Lab2: Final Amplifier (A5)



# Lab3: Compressor & Pulse-Diagnostics



# Lab4: Target-Area & Control Room



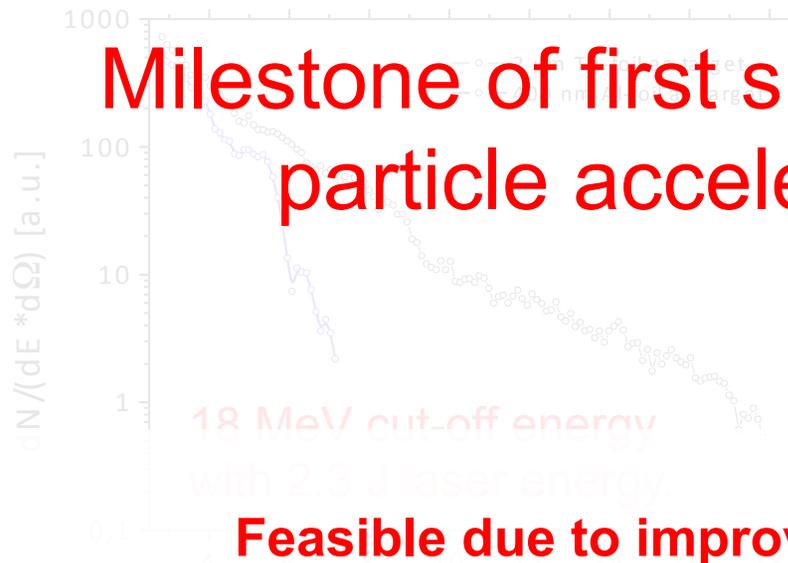
# Experimental Results: Particle Acceleration

Laser benchmark experiment:

TNSA with thin foils: proton acceleration.

2012:

Final proton energy spectra:



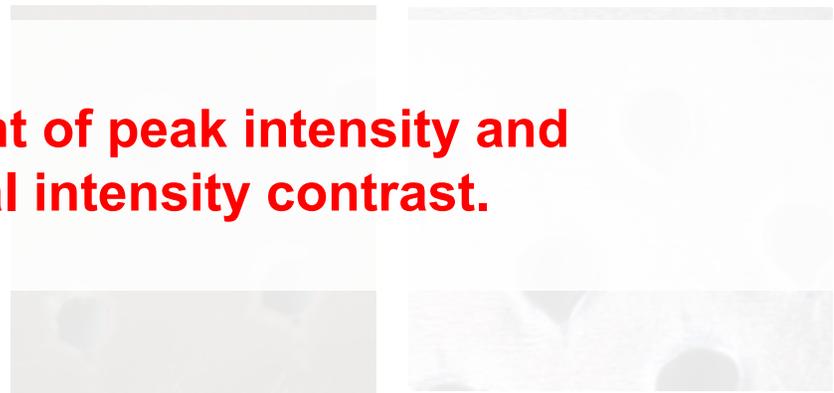
**Milestone of first successful experimental particle acceleration campaign !**

**Feasible due to improvement of peak intensity and enhancement of temporal intensity contrast.**

More than 1500 high energy shots on different materials (Cu, Al, Ag, Ta, Ti) and thicknesses (400 nm - 50 μm).



Target after the interaction:



**This year more than 7000 high energy shots in laser matter experiments !**

### Targets in 2012:

- february to march: thin foils
- april to july: water droplets
- august: sandwich foils
- in preparation: november to december: gas-jet

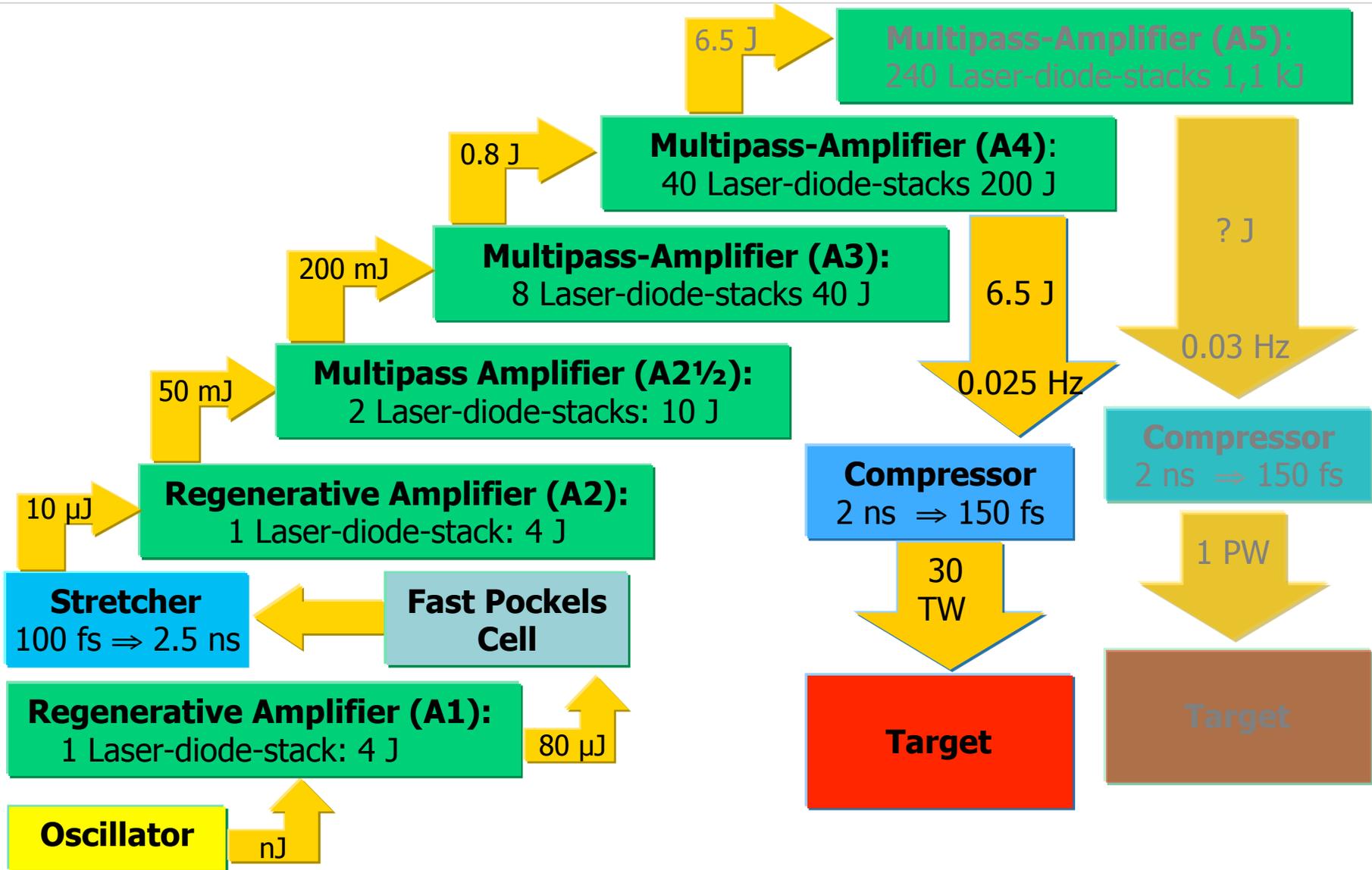
### Diagnostics:

- CR-39 Stack (energy, spatial distribution, ions)
- Multi-channel plate (online, energy, ions)
- Scintillation screen & gateable, fast CCD (online, spatial & energy distribution, ions)
- In-vaccum, soft X-ray camera & bent crystal (spectral & spatial resolution)
- $2\omega$  or  $3\omega$  online focal spot diagnostics
- target back-side deformation (Nomarski-Interferometer)
- Synchronized side-view (532 nm, 1 ns)
- in preparation: e<sup>-</sup>-diagnostics, 150 fs low-energy probe pulse unit, variable pre-pulse unit

- Introduction
- Optimizing Peak Intensity
- Optimizing Temporal Intensity Contrast
- Operation and Stability
- Amplifier Development
- Conclusion

- Introduction
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- Optimizing Temporal Intensity Contrast
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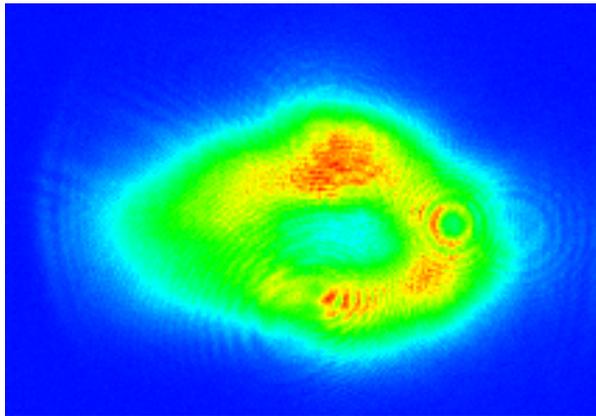
# Polaris Outline



- Introduction
- Optimizing the Peak Intensity
  - near-field profile A4
  - angular chirp compensation
  - adaptive optics
- Optimizing Temporal Intensity Contrast
- Operation and Stability
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# Near-field Profile of the A4

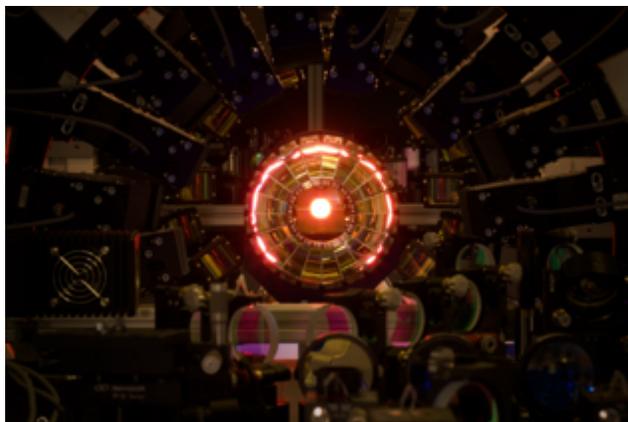
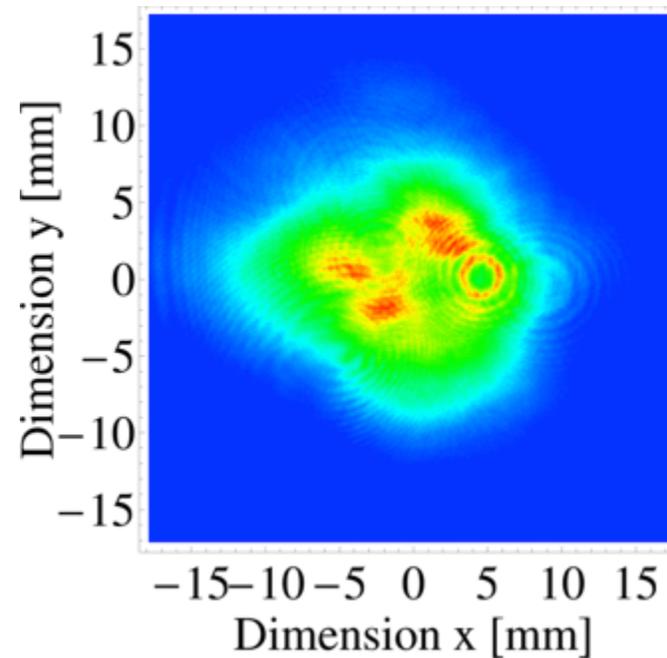
Old beam profile:



Problems:

- hole in the center
- „hot-spots“
- limits the focussability

Improved beam profile:

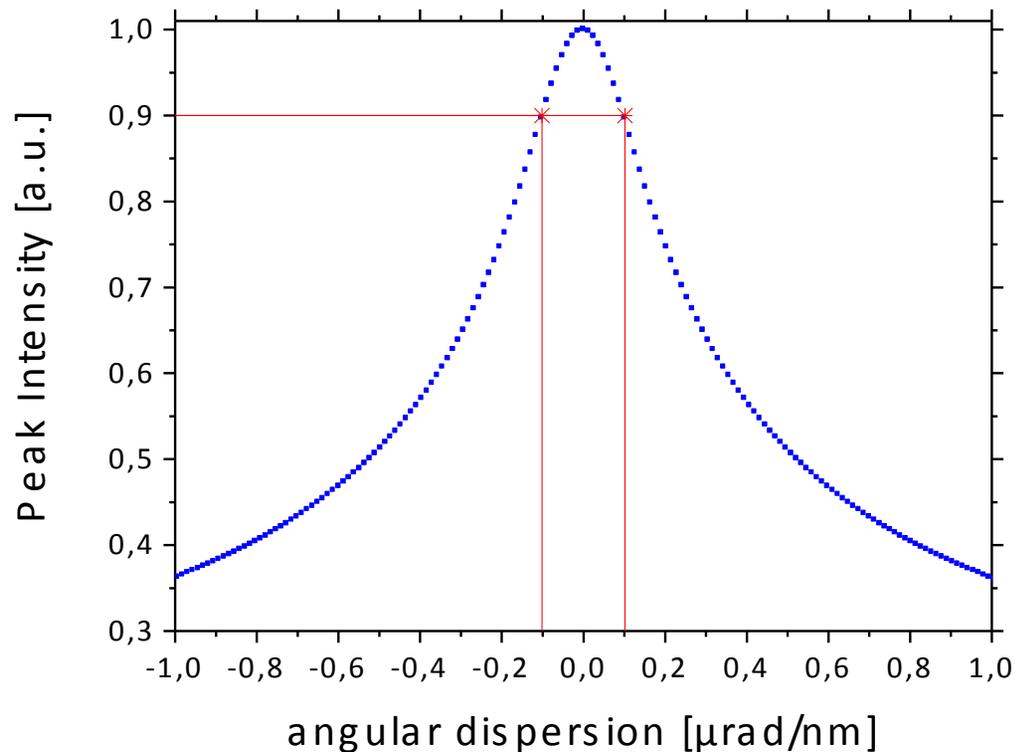


S. Keppler: Talk on 9/13 – 3 pm

- Introduction
- Optimizing the Peak Intensity
  - near-field profile A4
  - **angular chirp compensation**
  - adaptive optics
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# Motivation: Angular Chirp Compensation

Simulation: Peak intensity vs. Angular chirp:



Simulation for a  $f/2$ -focussed, 135-fs pulse with 140 mm diameter.

with angular chirp, the...

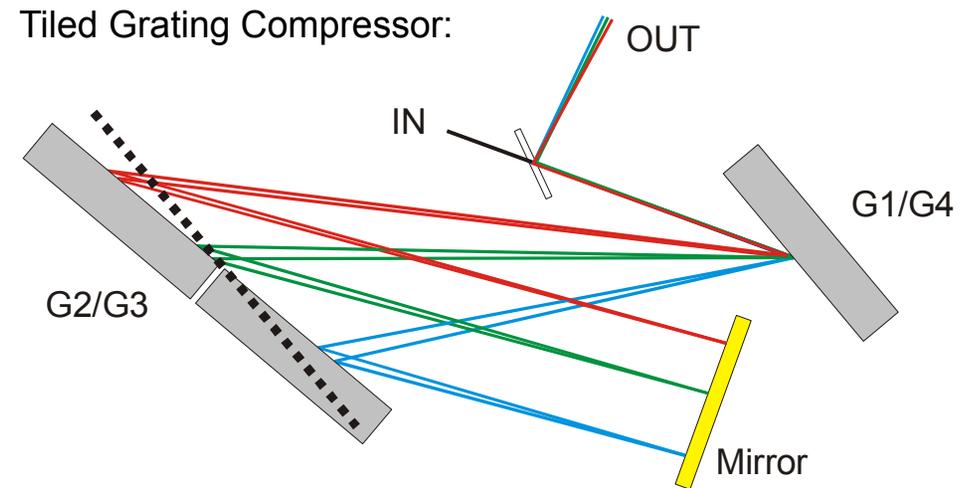
- focal spot size is enlarged
- pulse-front is tilted
- pulse duration is increased and a function of propagation distance

Formerly used method with a cw-laser did not measure the pulse itself.  
Accuracy  $\sim 0.1 \mu\text{rad/nm}$

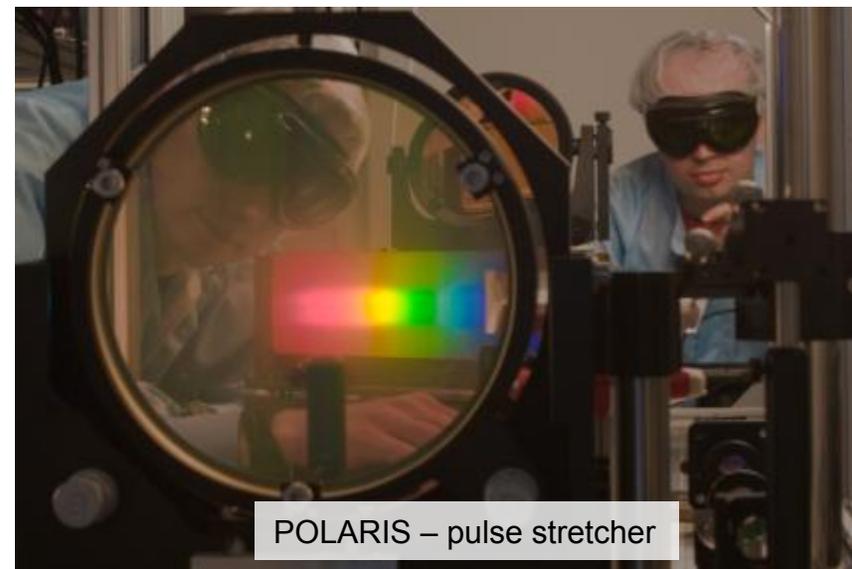
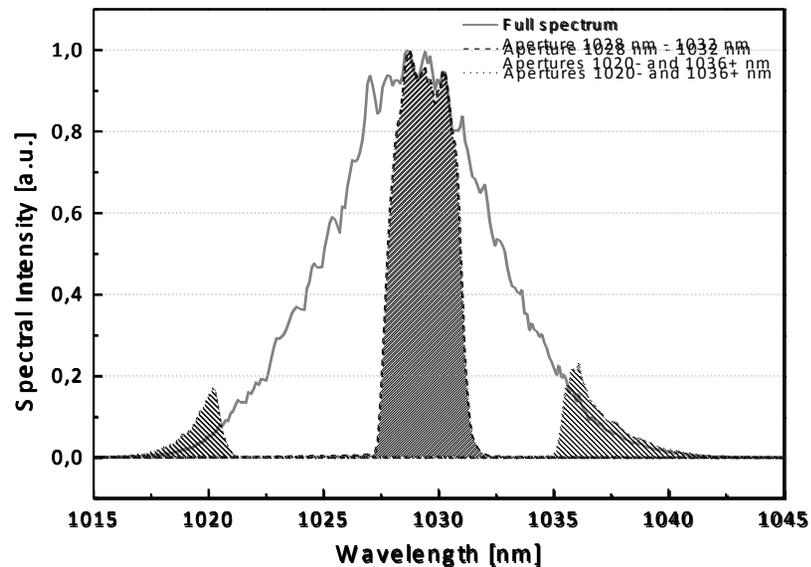
**The measurement of the laser pulses becomes very important!** (contrast issues & wedged optics)

# Measuring Angular Chirp with a TG-Compressor

**Idea:** Measure the propagation direction (far-field position) of 3 components of the laser pulse!

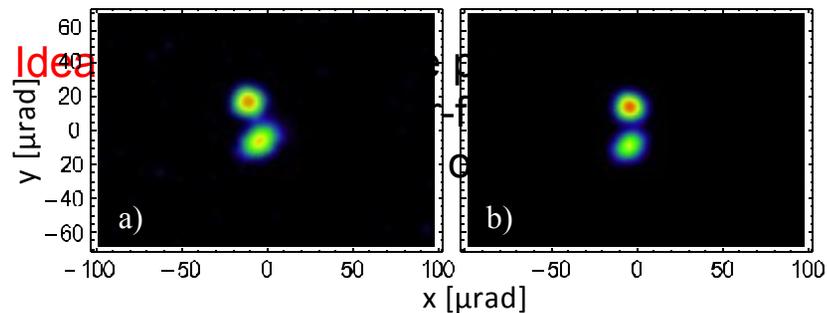


Spectral modification inside the stretcher:

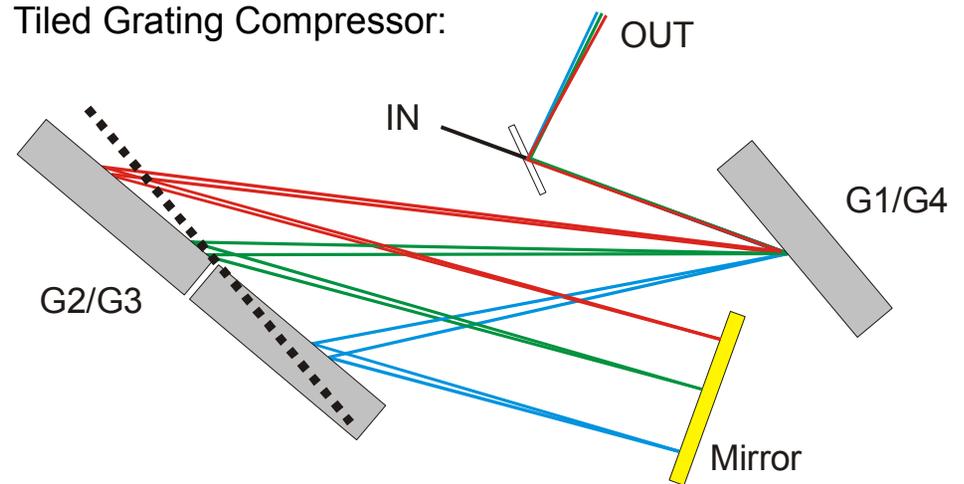


# Measuring Angular Chirp with a TG-Compressor

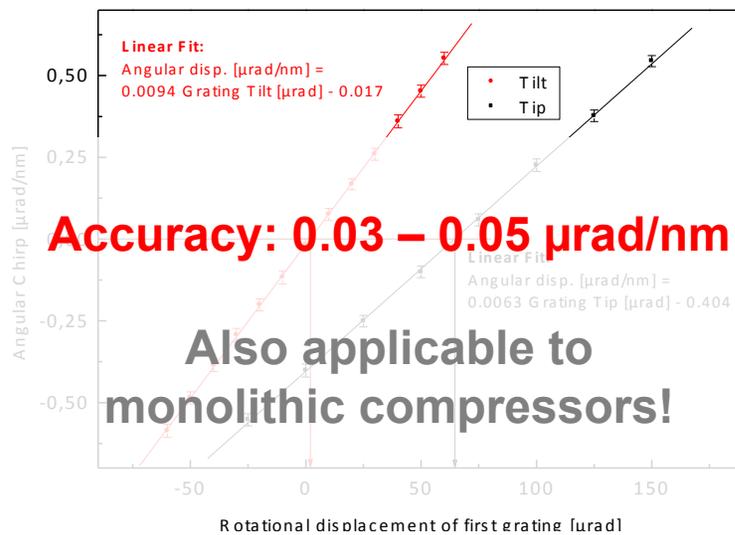
Measuring focal spot distance:



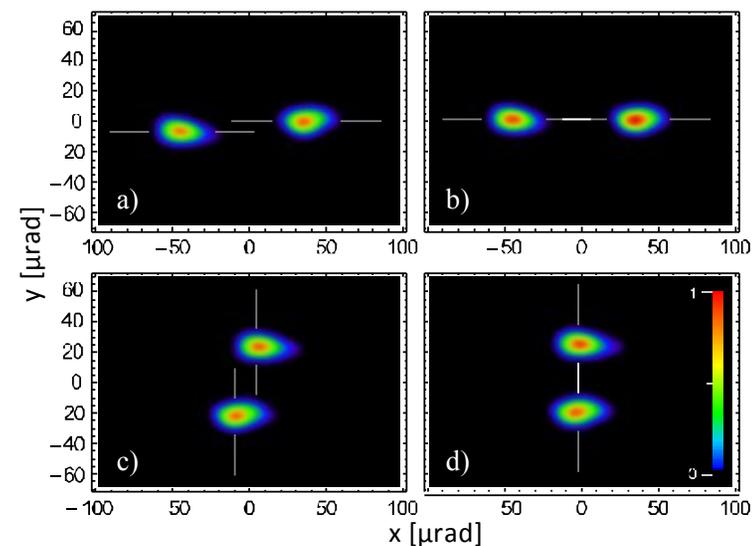
Tiled Grating Compressor:



Angular chirp vs. grating rotation:



Alignment of the tiled grating:

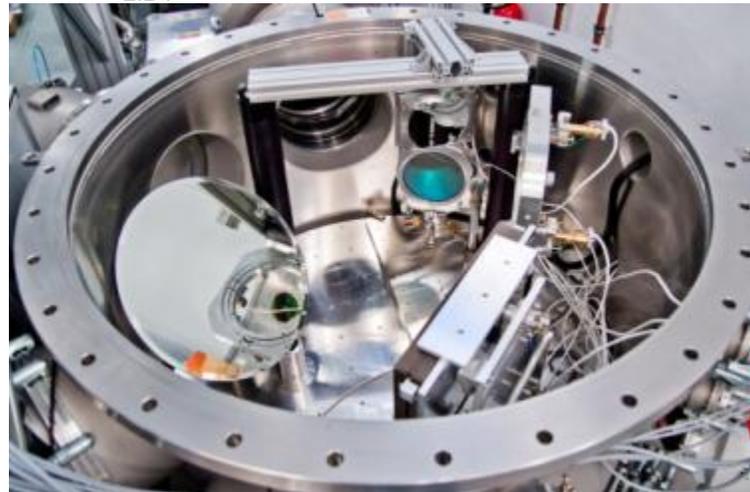


- Introduction
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  - near-field profile A4
  - angular chirp compensation
  - **adaptive optics**
- Optimizing Temporal Intensity Contrast
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# Adaptive Optics System for Wavefront Smoothing

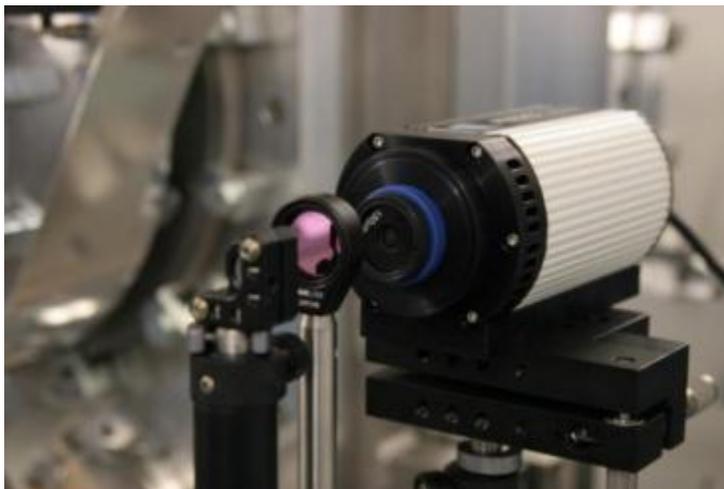
## NightN 6" deformable mirror

- high damage threshold ( $E_{\text{LIDT}}=1\text{J}/\text{cm}^2$ )
- 48 actuators
- Stroke:  $6\mu\text{m}$



## Phasics wavefront sensor SID4 HR

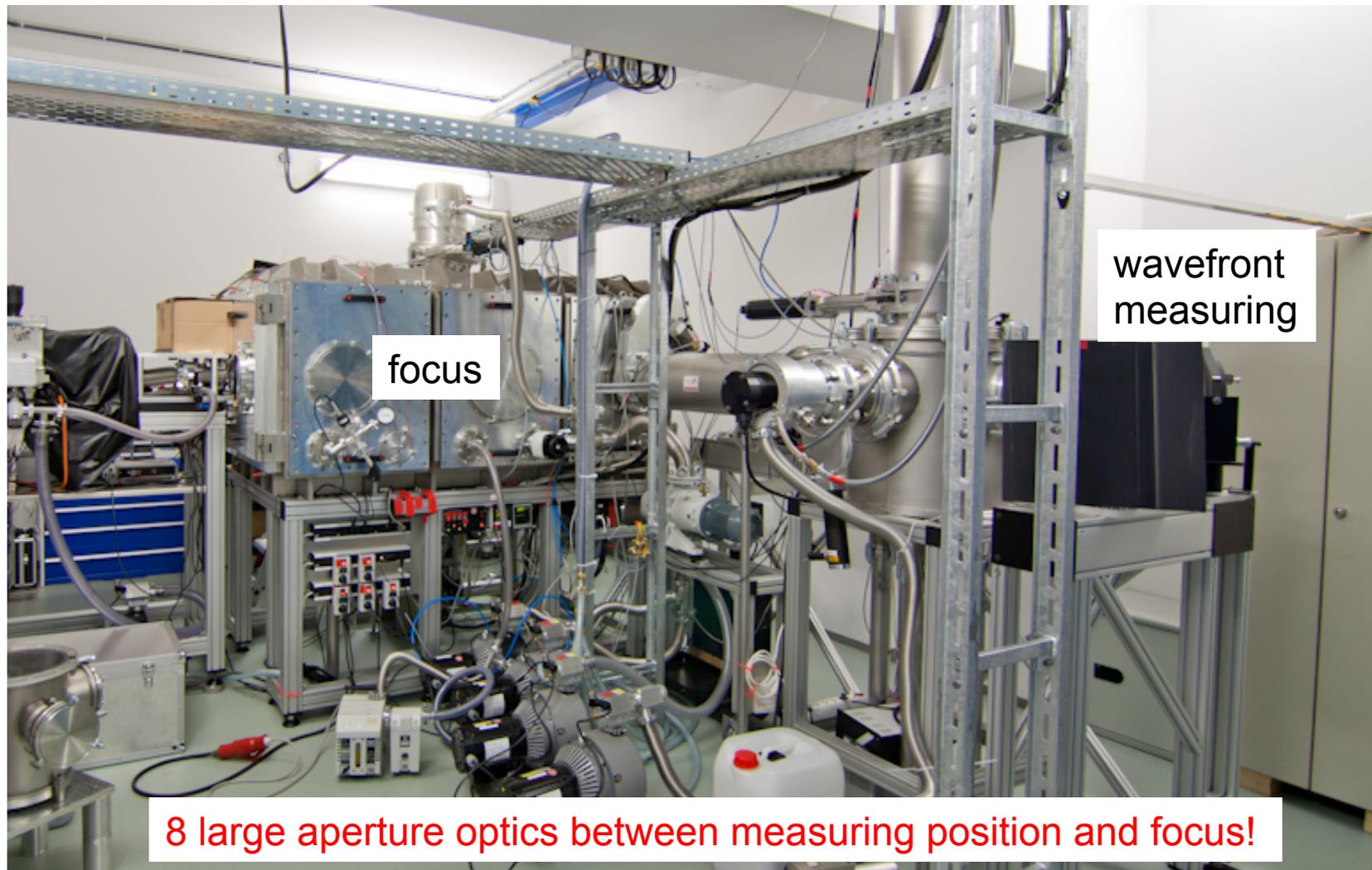
- WFS 0.4" free aperture
- Based on lateral shearing interferometry (300 x 400 sampling points.)



DM is imaged to the WFS by a specially corrected telescope.

# Measurement setup

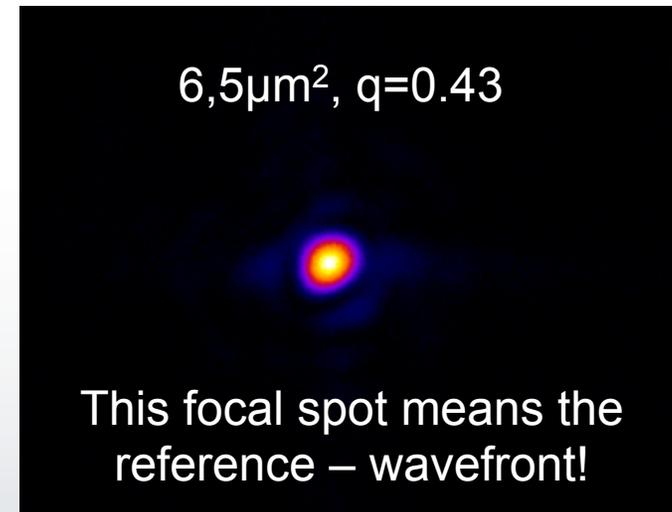
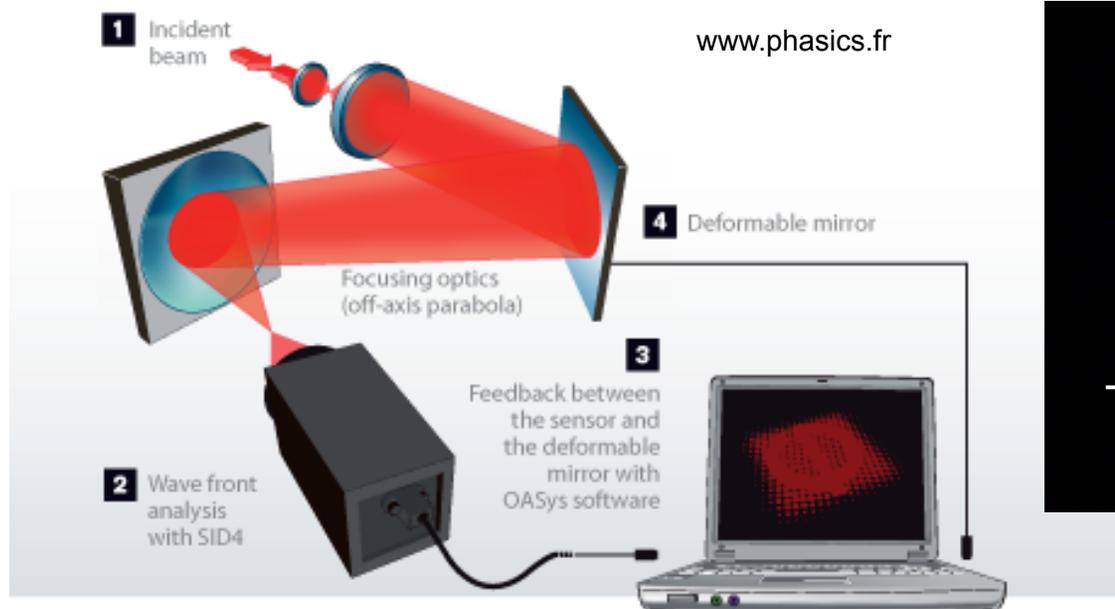
Goal: Smooth wavefront behind the focussing parabola.



# 1<sup>st</sup> step: flatten the wavefront of a reference pulse

- Reference Pulse:
- A2 with 1Hz repetition rate (spatial: TEM<sub>00</sub>-mode)
  - beam diameter expanded to illuminate the complete beamline
  - Pulse energy massively decreased (ND-filters)

Best focal spot:

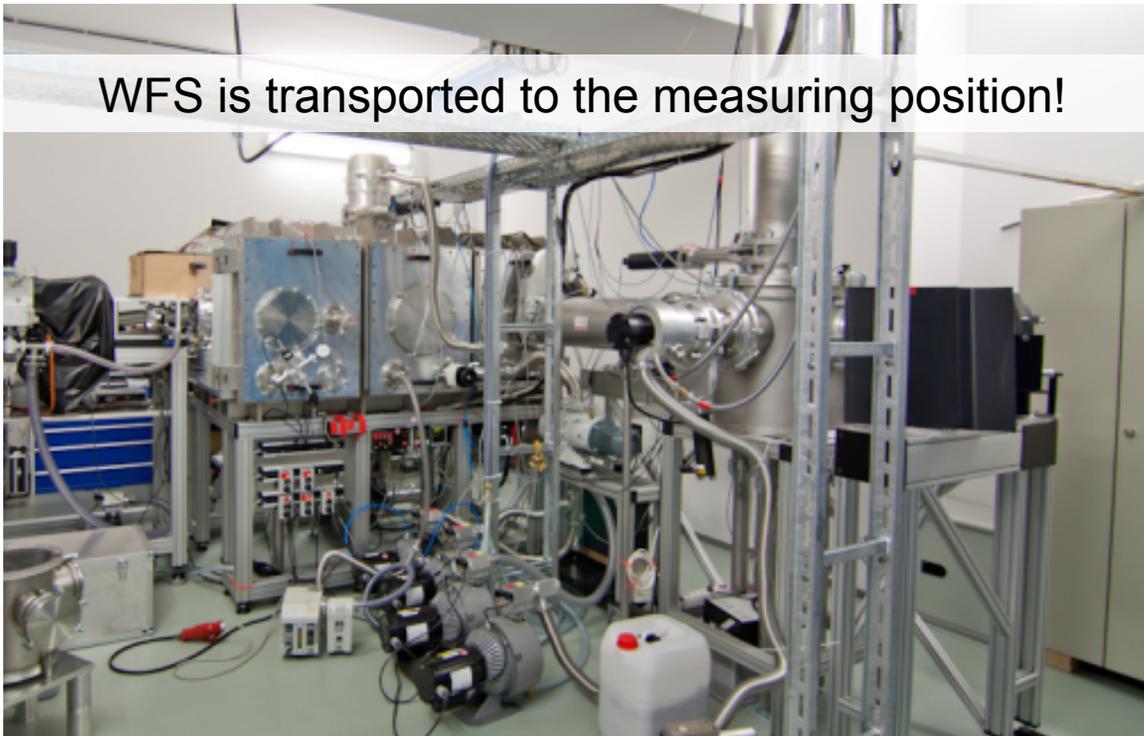


Correct the wavefront for all aberrations originating in the laser amplifiers, transport beamline-mirrors and the final focussing optics!

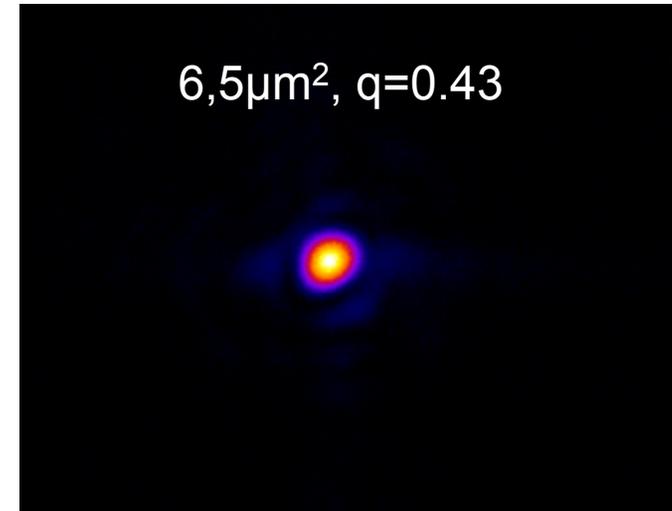
2<sup>nd</sup> step: fix the wavefront of a reference pulse

All parameters held constant during this procedure!

WFS is transported to the measuring position!



Best focal spot:

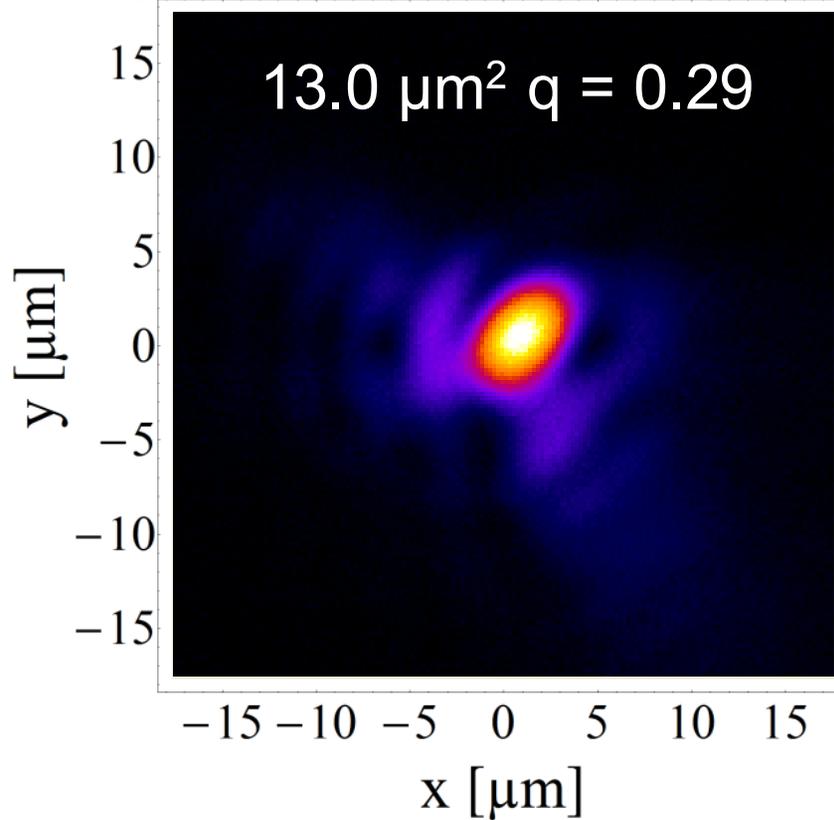


**Measured wavefront is now the reference for the best focal spot !**

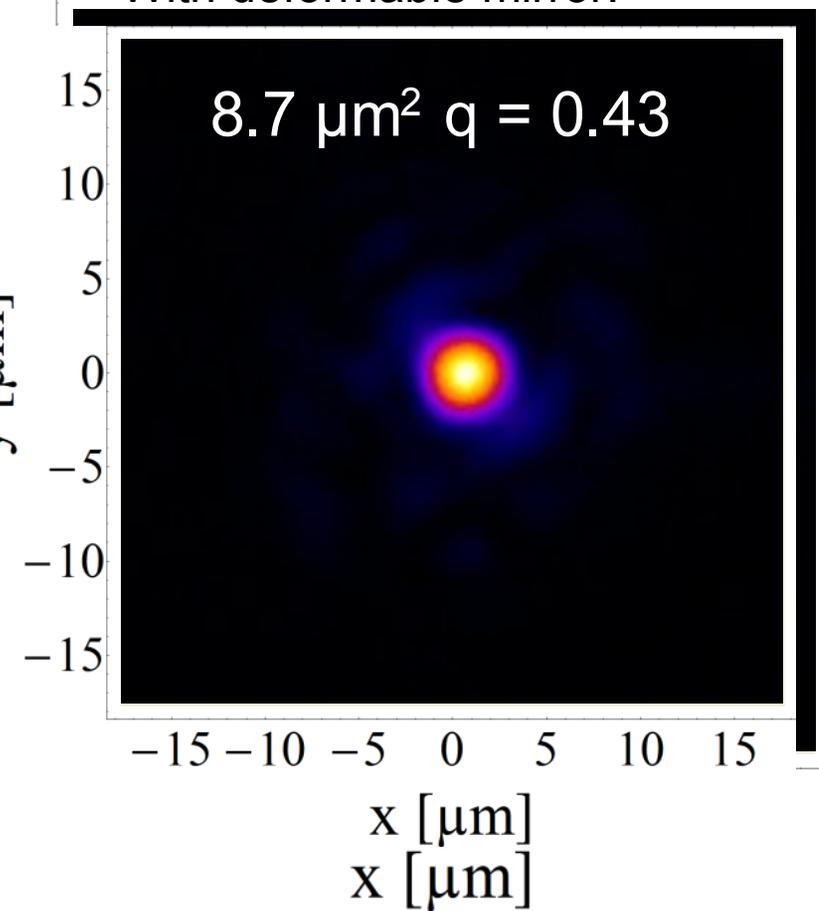
# A4 focal spot with optimized wavefront

With plane beamline-mirror:

$A_{FWHM} = 8.7 \mu\text{m}^2$



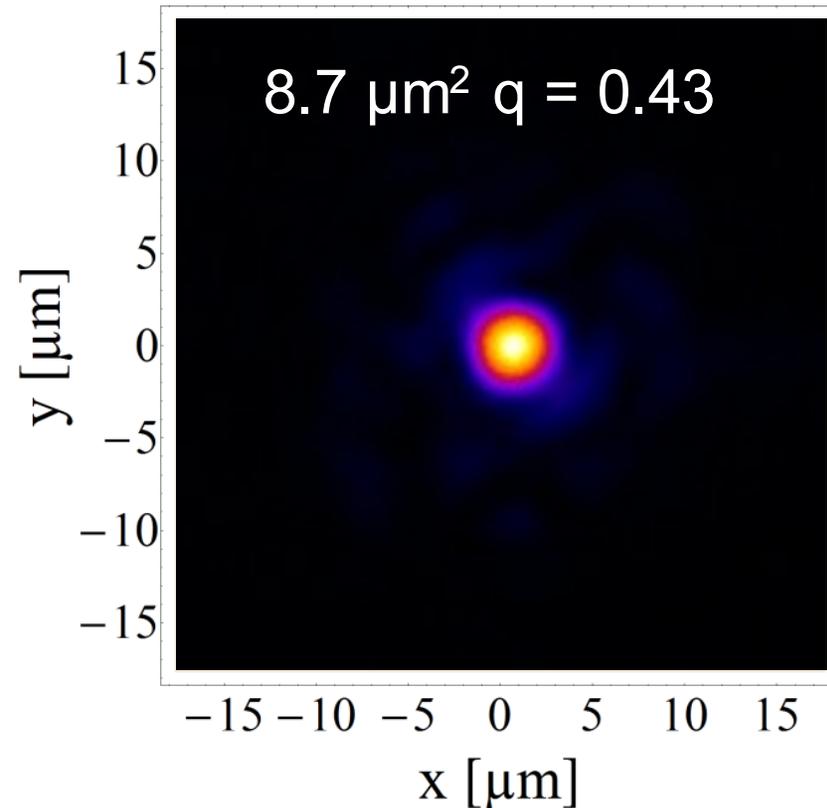
With deformable mirror:



q... means the energy-content within the FWHM-area

# Conclusion Adaptive Optics

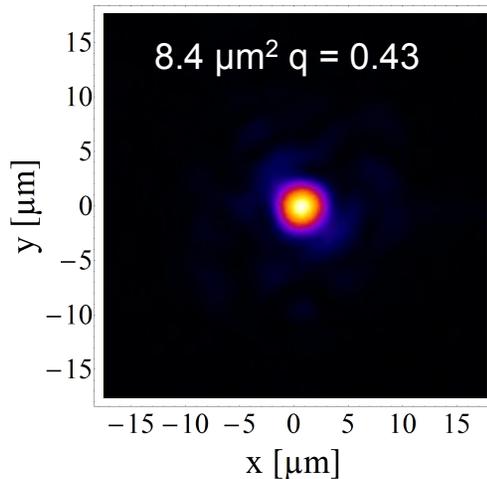
**Peak intensity more than doubled !**



- position accuracy is important for reproducibility
- time saving in daily operation

# Conclusion “Optimizing Peak Intensity”

Focal Spot:



$$t_{FWHM} = 164 \text{ fs}$$

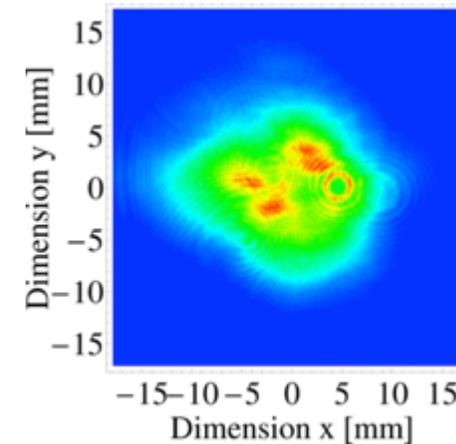
$$q = 0.43$$

$$A_{FWHM} = 8.4 \mu\text{m}^2$$

$$E_{\text{pulse}} = 6.5 \text{ Joule}$$

$$\eta_{\text{Compressor}} = 0.63$$

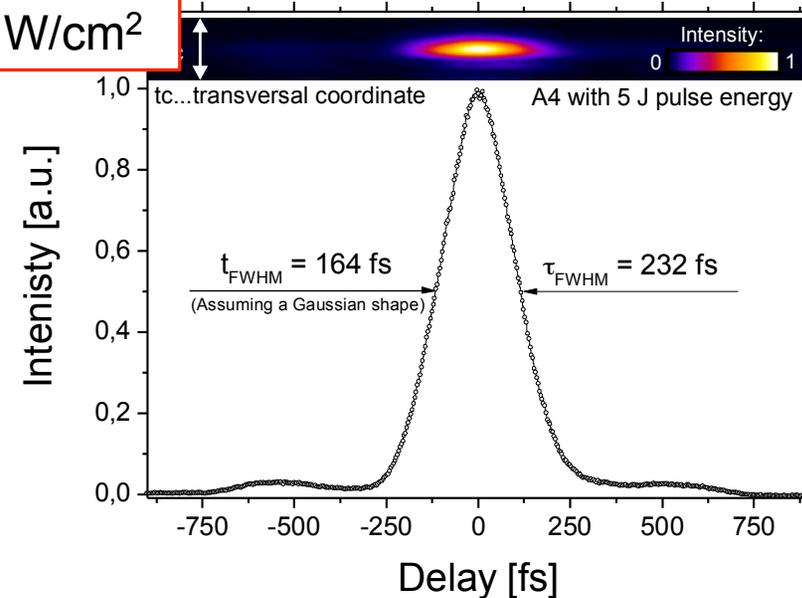
Near-field profile:



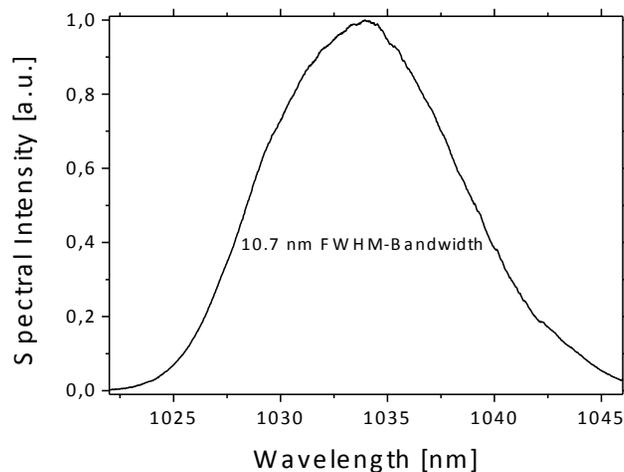
$$I_{FWHM} = 2.6 \times 10^{20} \text{ W/cm}^2$$

$$I_{\text{Peak}} = 5.1 \times 10^{20} \text{ W/cm}^2$$

pulse duration:



Spectral intensity:

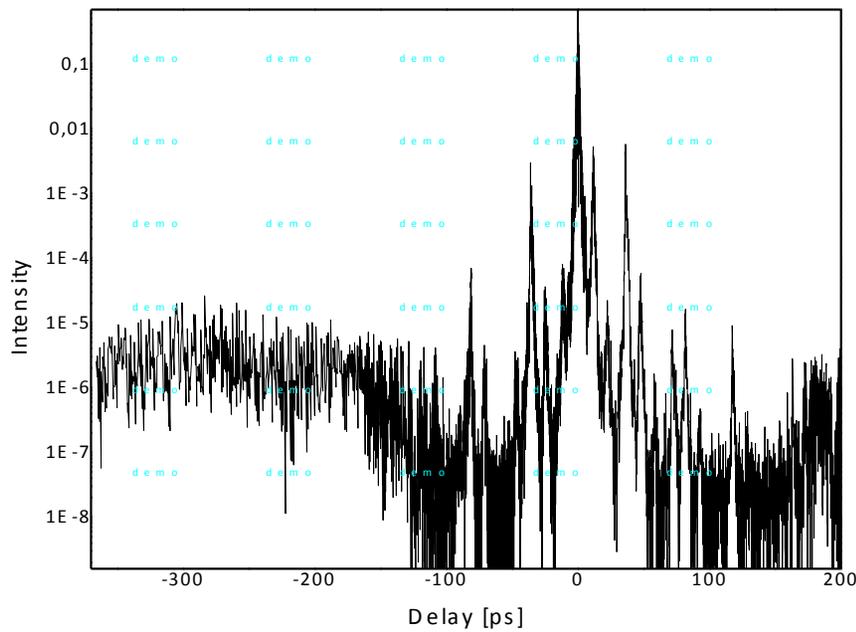


- Introduction
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- **Optimizing Temporal Intensity Contrast**
- Amplifier Development
- Operation and Stability
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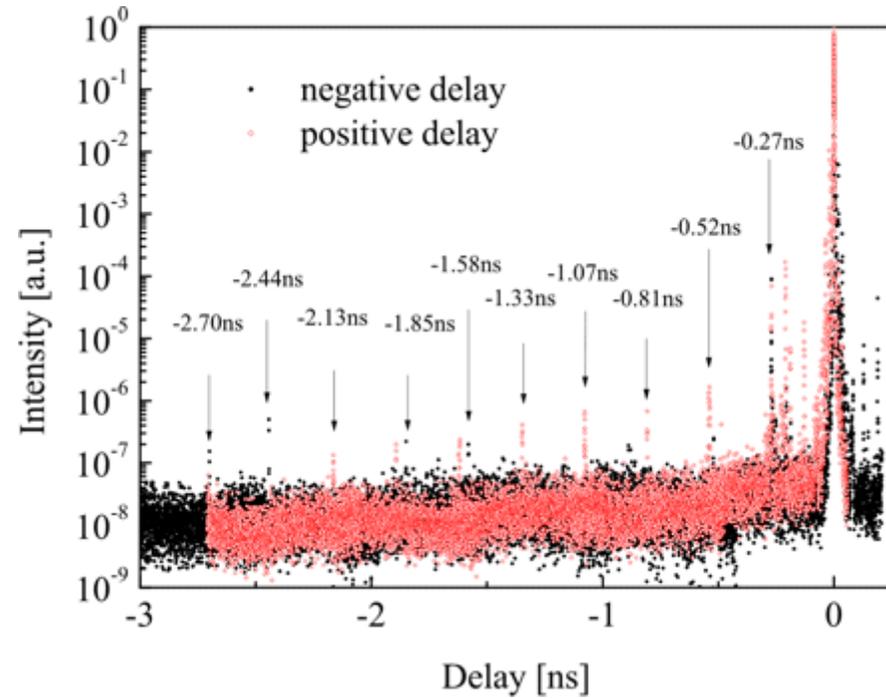
# Where did we started?

## First measurements:

### Picosecond timescales:

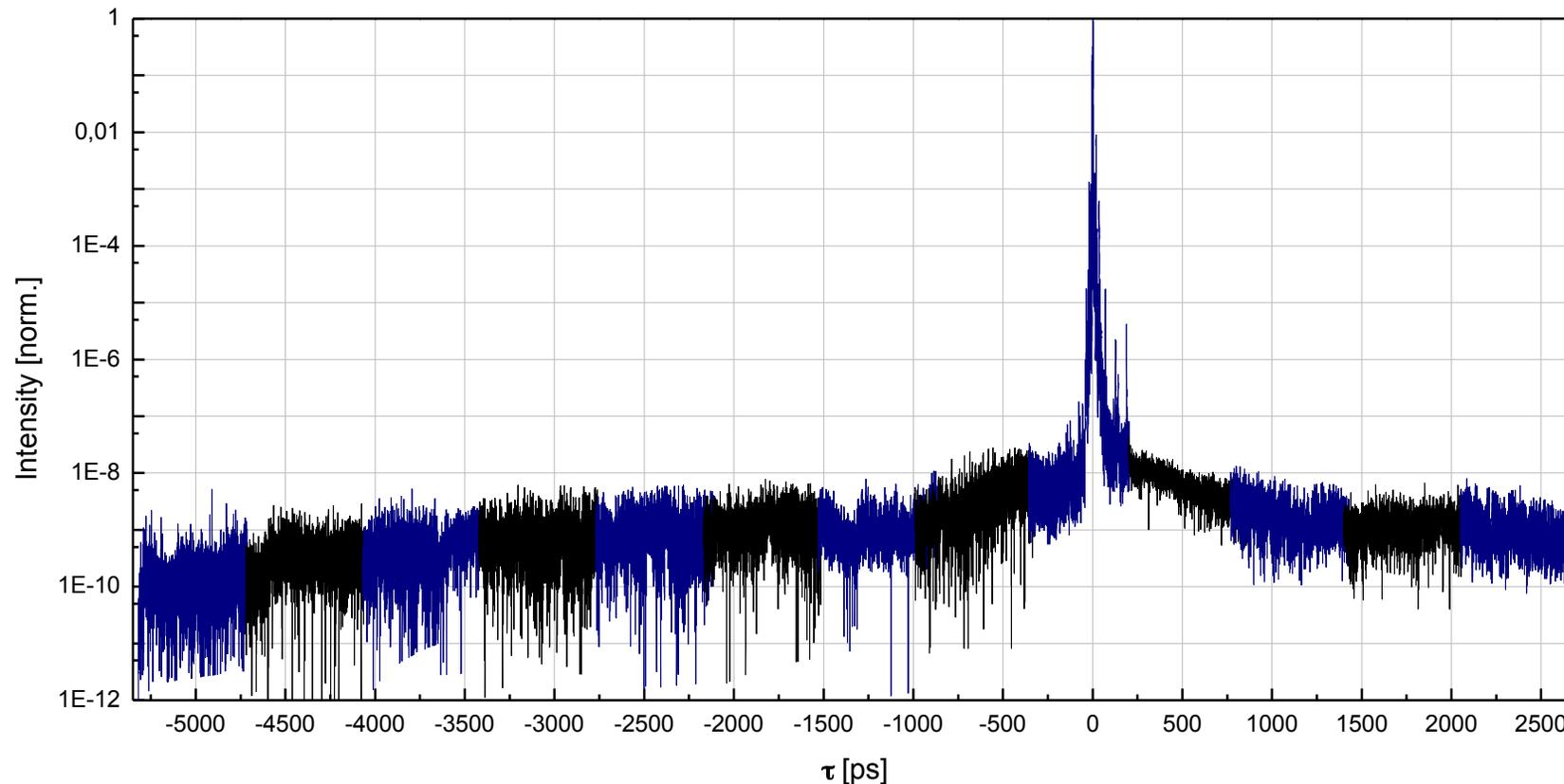


### Nanosecond timescales



# Optimizing the Nanosecond Contrast

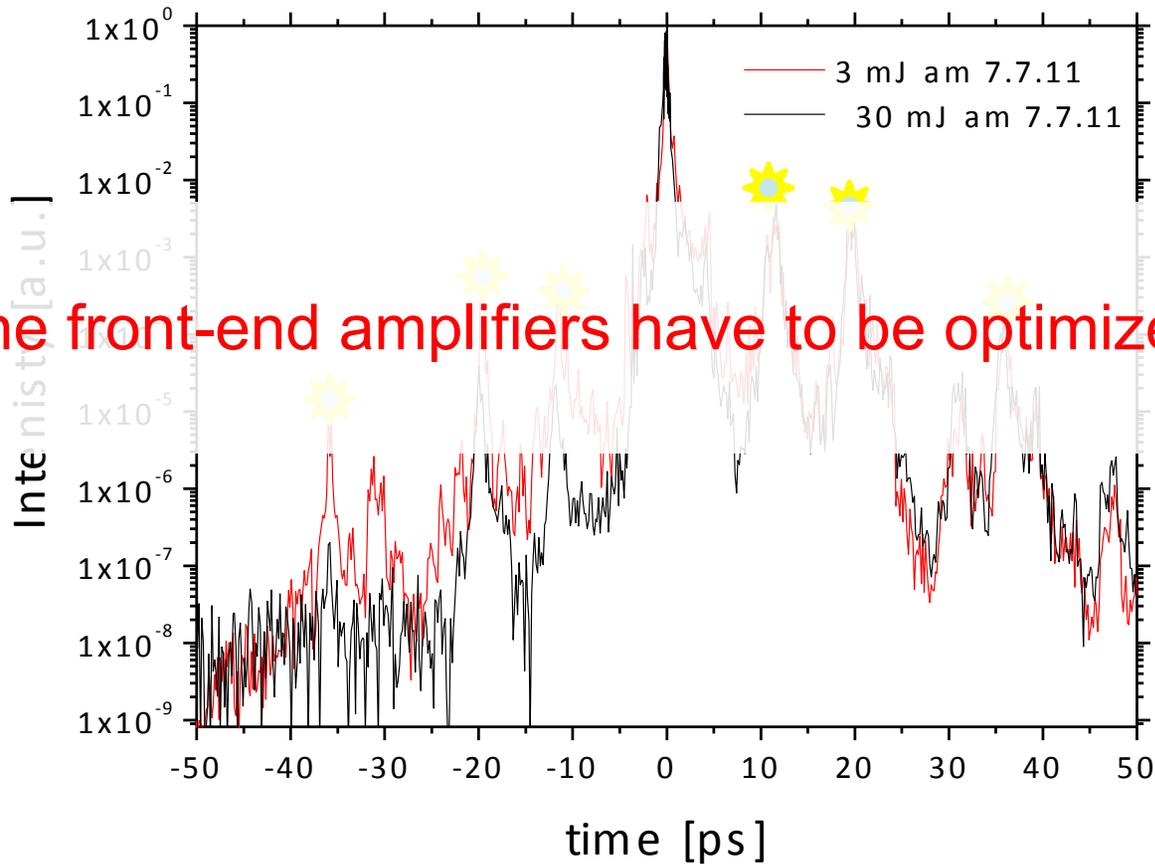
- Synchronization of the oscillator and the regenerative amplifiers
- Artifacts due to the measurement setup itself (Sequoia).
- Installation of a fast Pockels Cell ( $\tau_{\text{Rise}} = 200 \text{ ps}$ ).



250 fs sampling with 9 ns scanning range means 10 hours measurement @1Hz.

# Measuring the Picosecond Contrast

Pre- and postpulses @ 12, 20 & 36 ps !



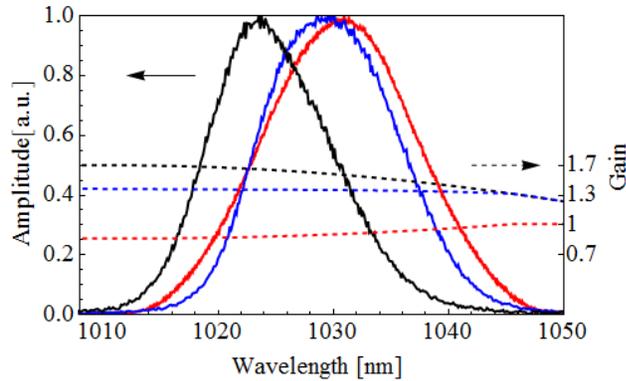
12 ps: half-wave-plates

20 ps: MO-wave-plates  
for spectral shaping

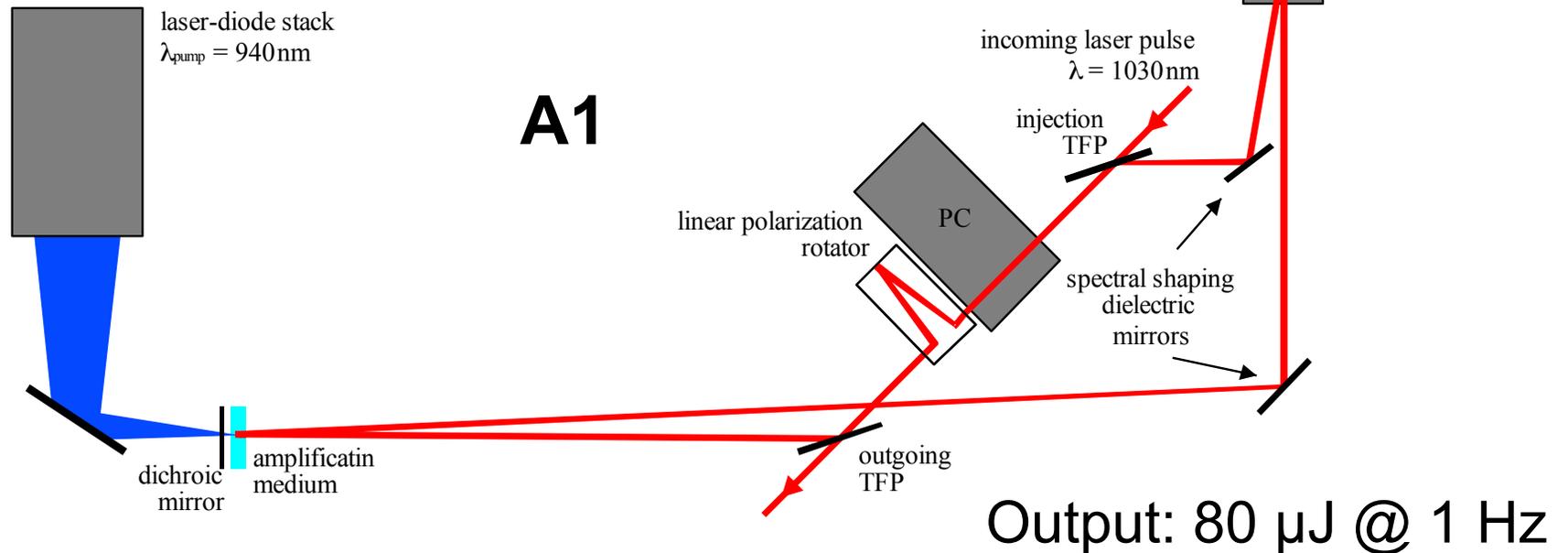
**The front-end amplifiers have to be optimized regarding contrast !!**

# Contrast-Modification of the A1 & A2

Spectral shaping mirrors:

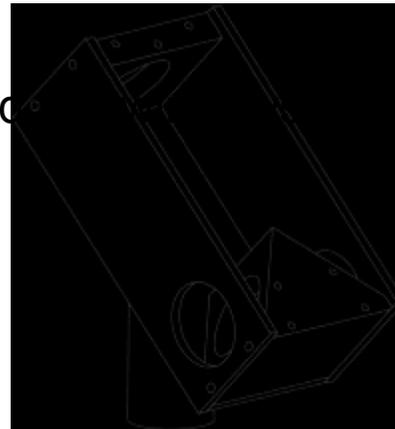
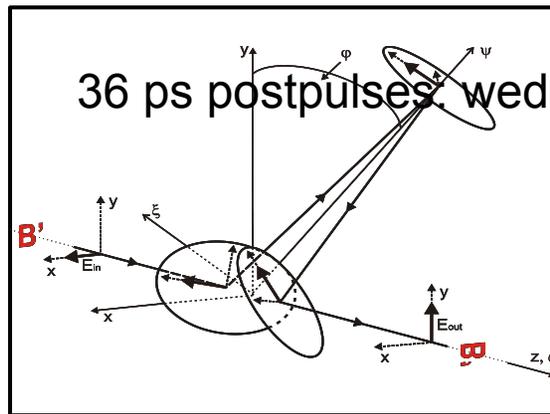


- regenerative fs-amplifier
- 25 round-trips
- TEM<sub>00</sub>-mode
- 19 nm FWHM-bandwidth

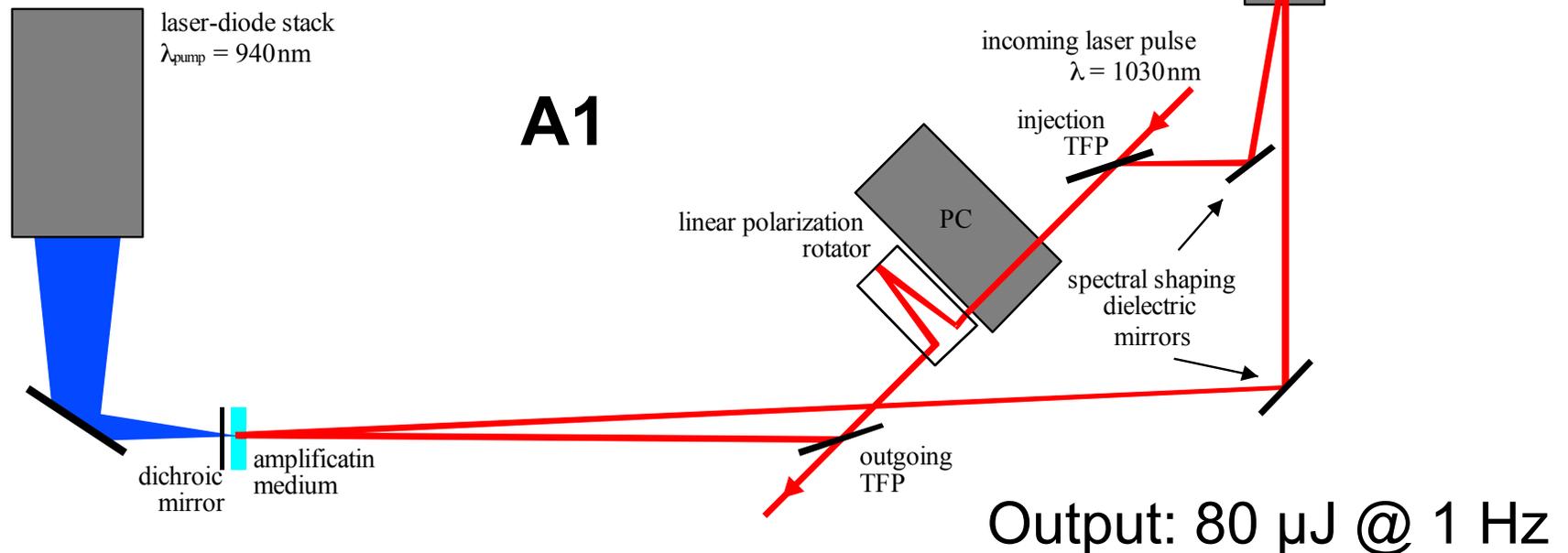


# Contrast-Modification of the A1 & A2

Purely reflective polarization rotator:



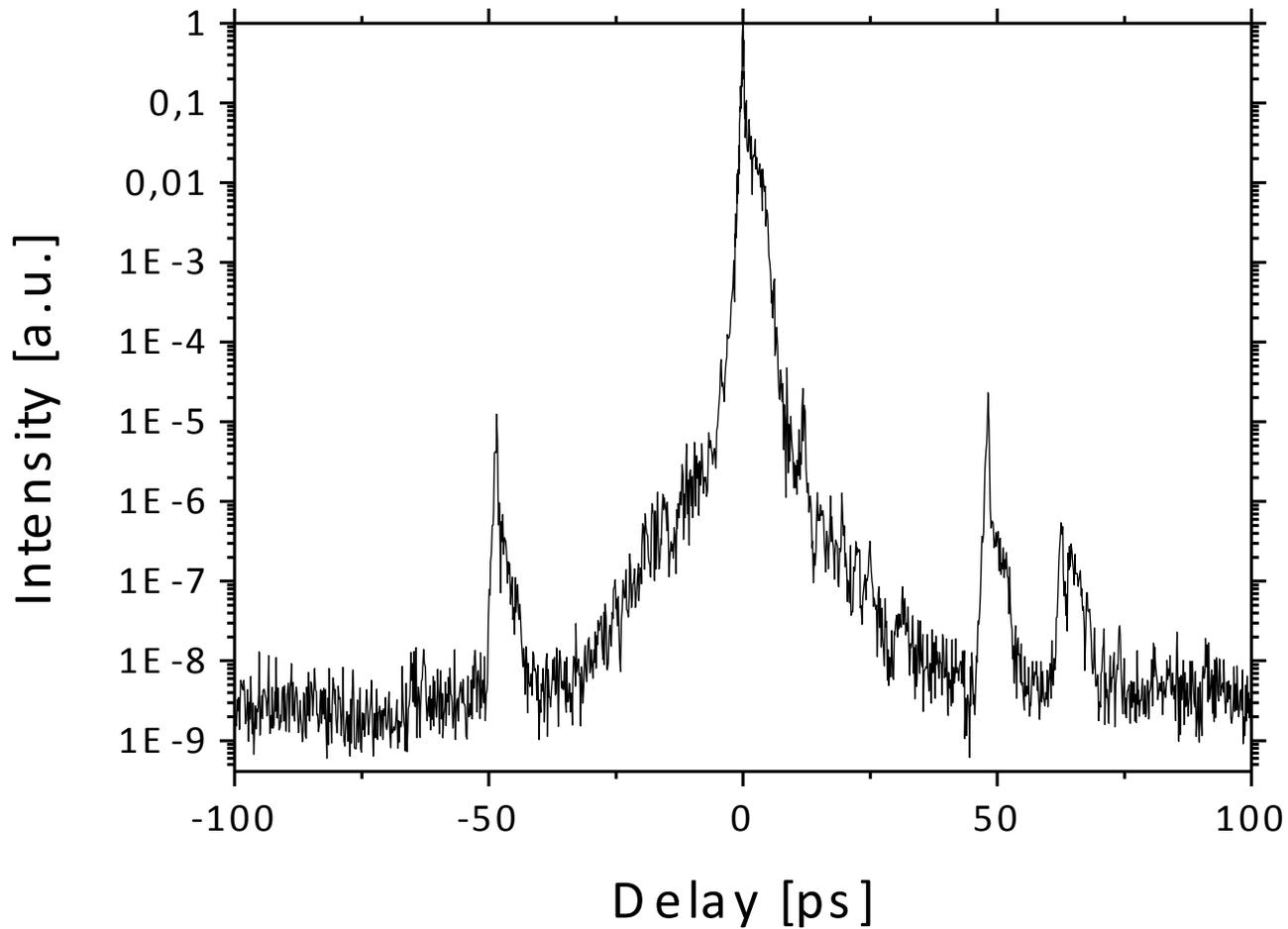
- regenerative fs-amplifier
- 25 round-trips
- TEM<sub>00</sub>-mode
- 19 nm FWHM-bandwidth



# Furthermore: Stray Light in Amplifiers



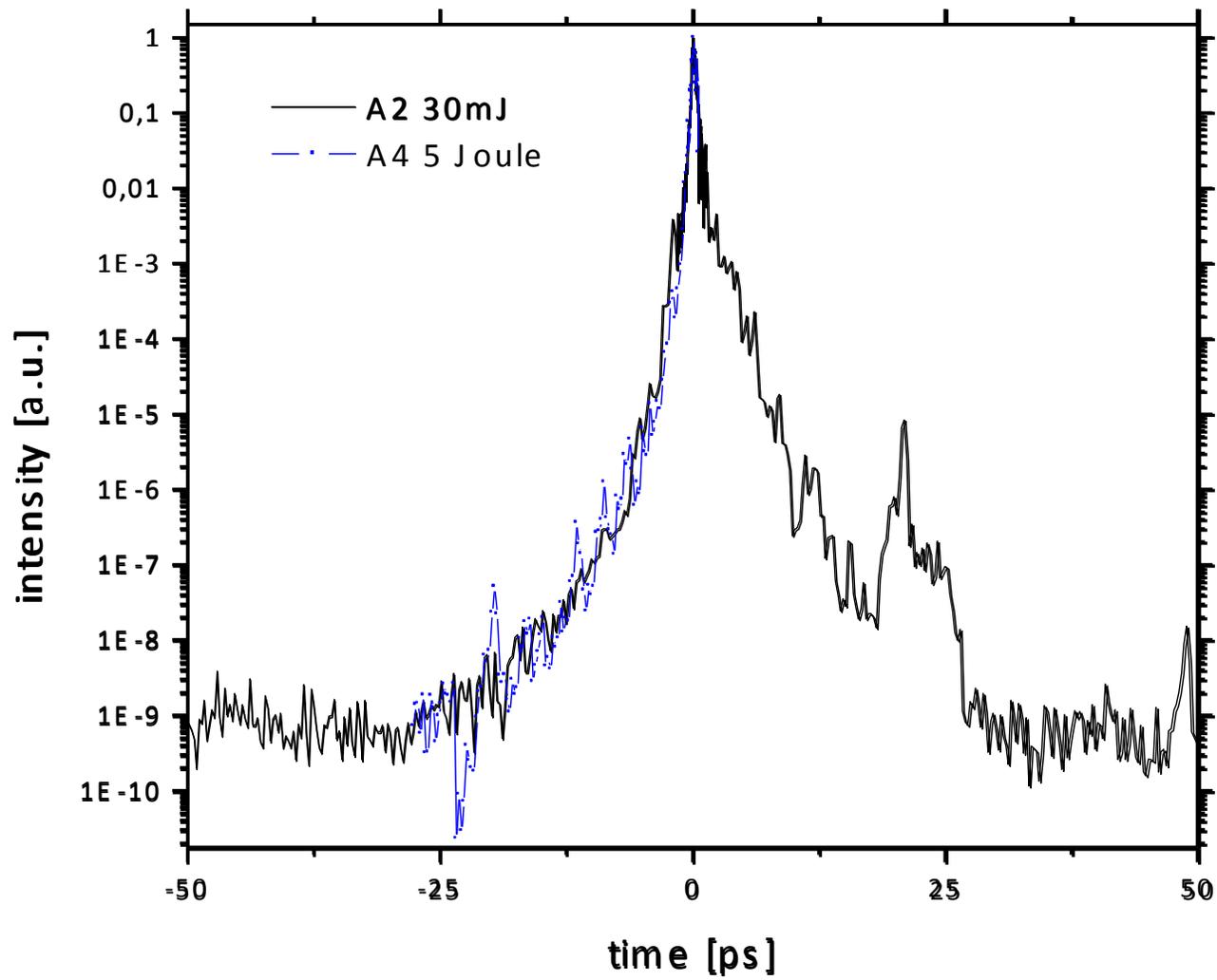
e.g.: active Material in A2 generates pre- and post-pulses due to stray-centers or misalignments.



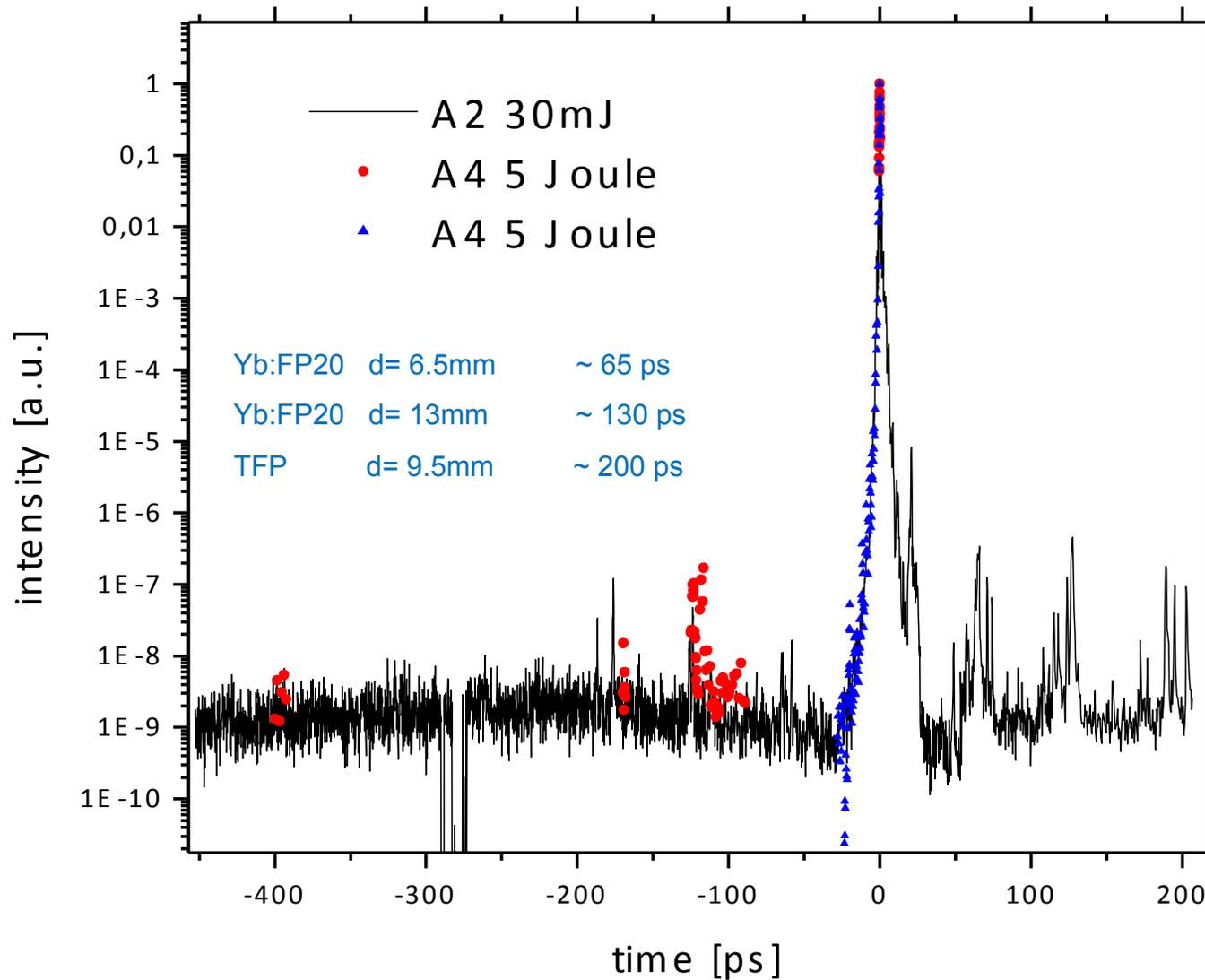
# Picosecond Contrast with optimized Front-End



Strong reduction of pre- and postpulses!



...some work to do

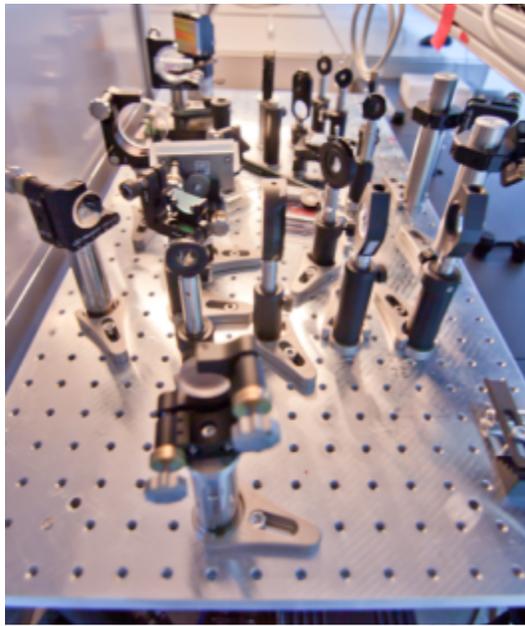


# Outlook: Contrast Improvement with Double CPA

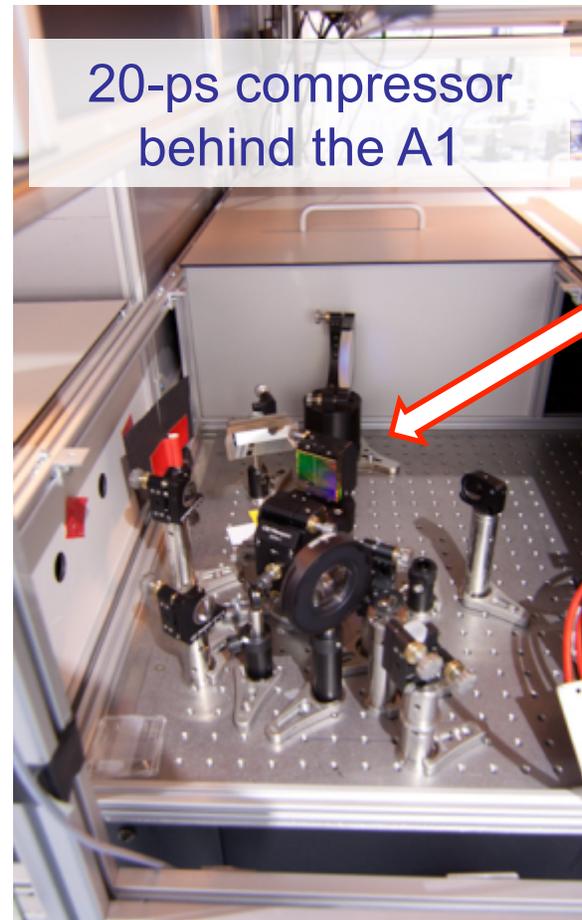
→ mJ-fs pulses are required for further contrast-enhancement techniques!  
e.g. XPW, saturable absorber, ...

Already set up:

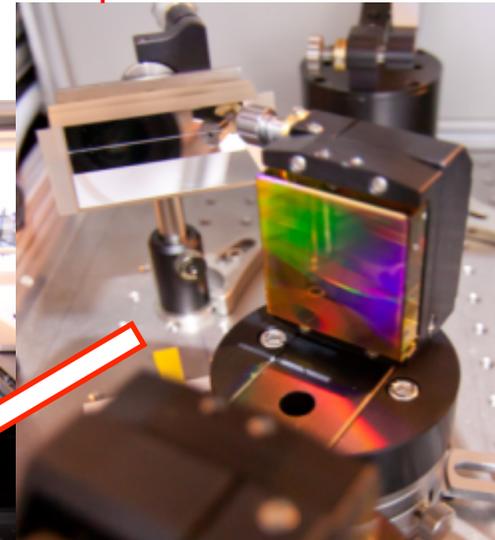
Stretcher & Compressor



20-ps stretcher  
behind the MIRA



20-ps compressor  
behind the A1



- Introduction
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- Optimizing temporal intensity contrast
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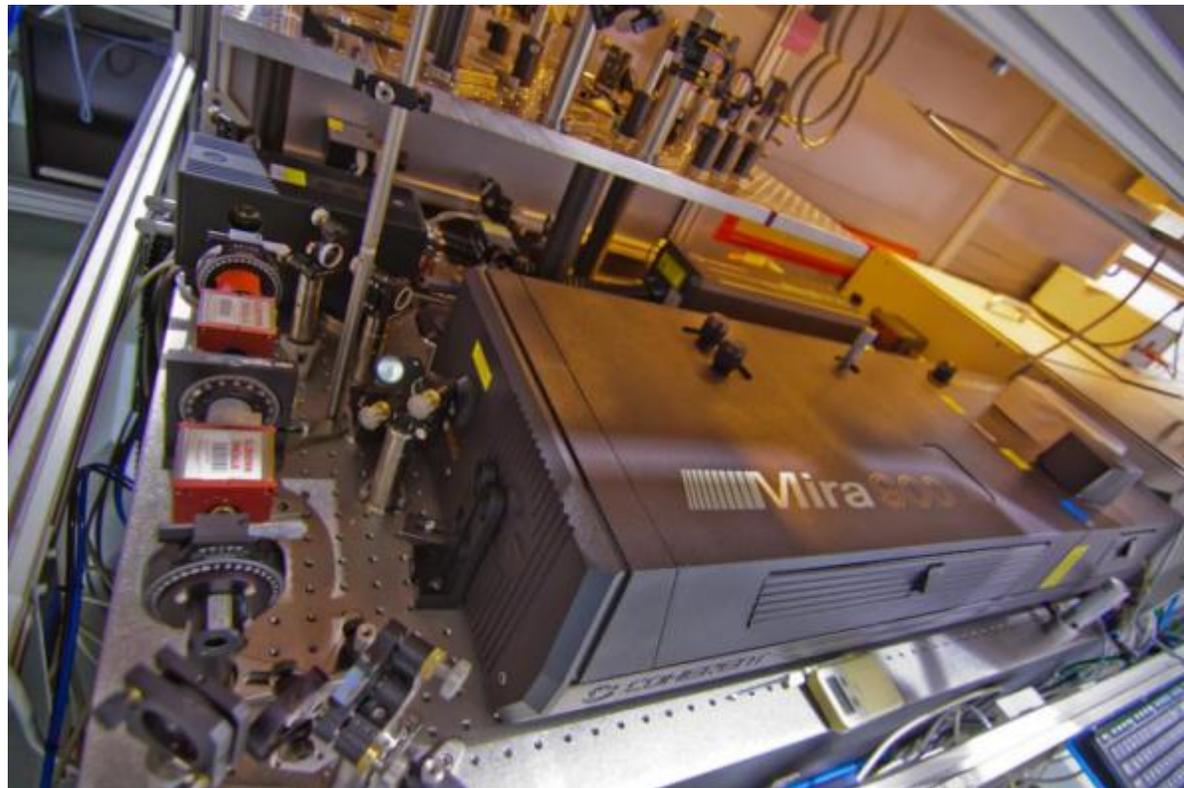
# Oscillator & Stability Improvement

The MIRA was refurbished:

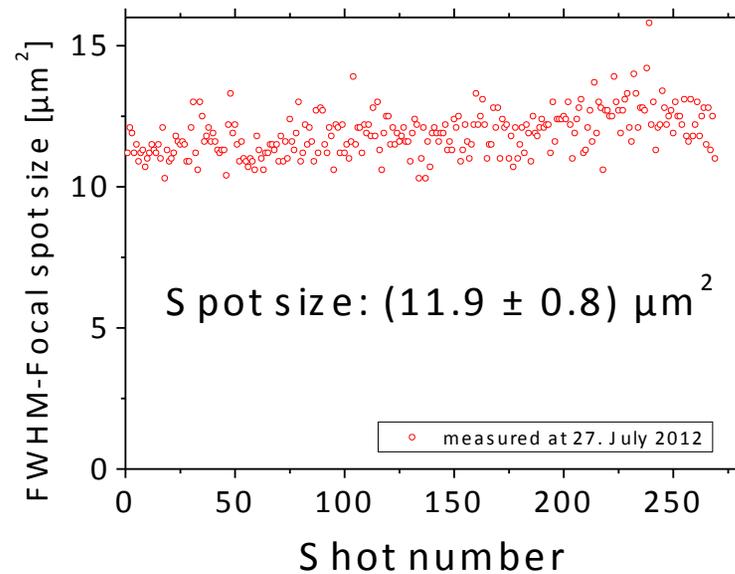
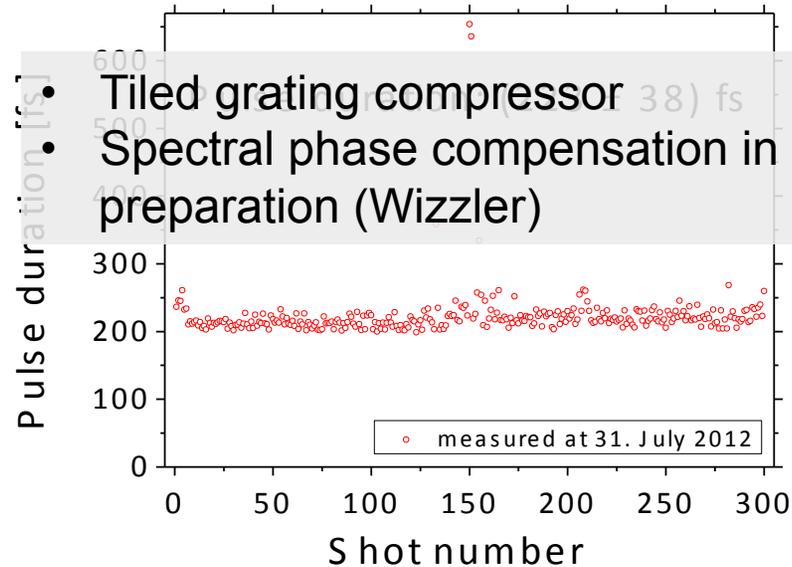
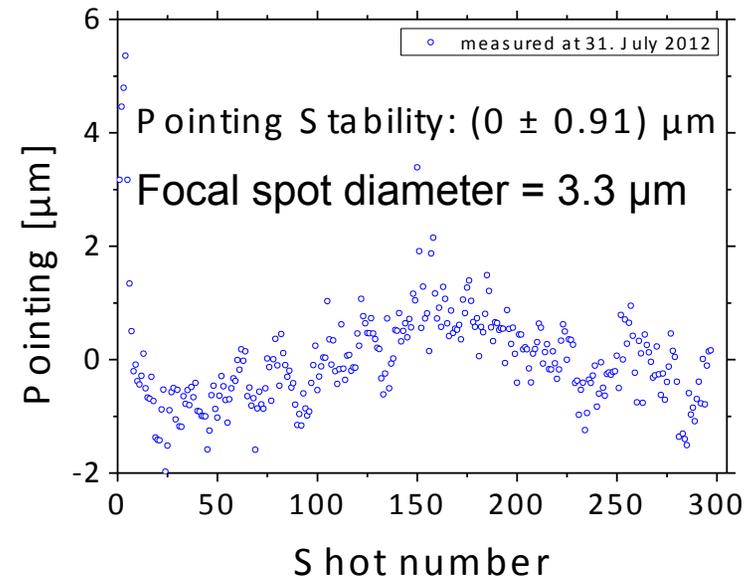
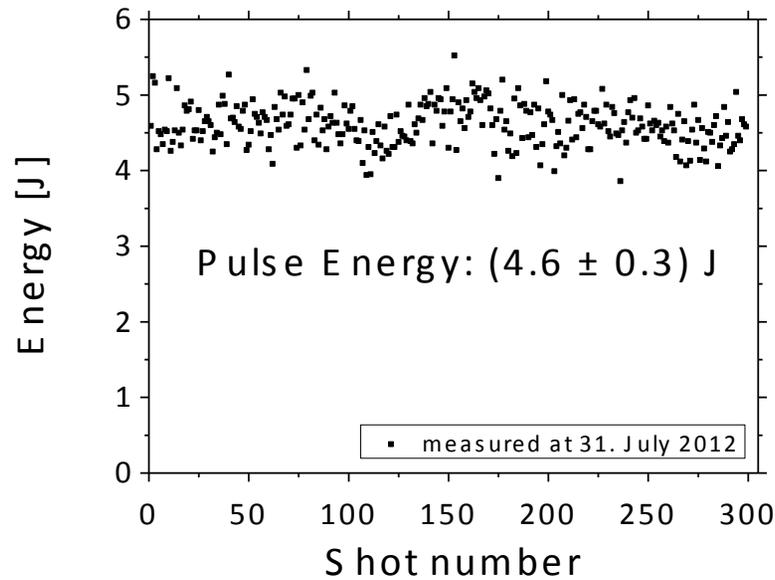
- Mirror upgrade after 10 years operation (extended long wavelength@1030 nm)
- Verdi V10: new head & pump diodes
- output power doubled and bandwidth improved
- cw: 750 mW (before: 470 mW)
- modelocking: depending on bandwidth up to 520 mW (before: 250 mW)

Stability improvement:

- all amplifiers are boxed
- laser operation is completely motorized

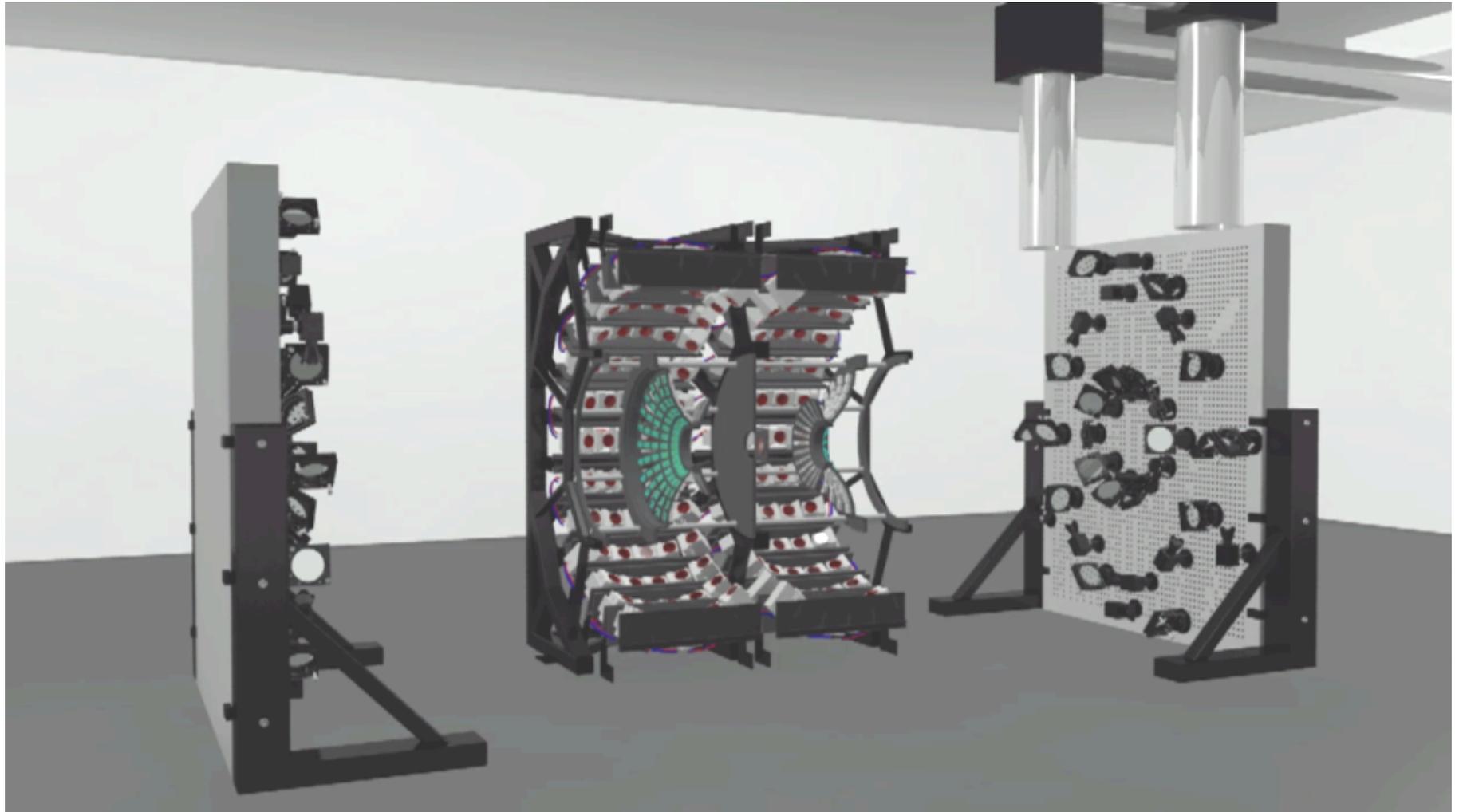


# Pulse Parameters during Operation



- Introduction
- Optimizing the Peak Intensity
- Optimizing Temporal Intensity Contrast
- Operation and Stability
- **Amplifier Development**
  - **A5**
  - Reconstruction of A3
  - Cryo burst laser system
  - A4 pump engine extension
- Conclusion

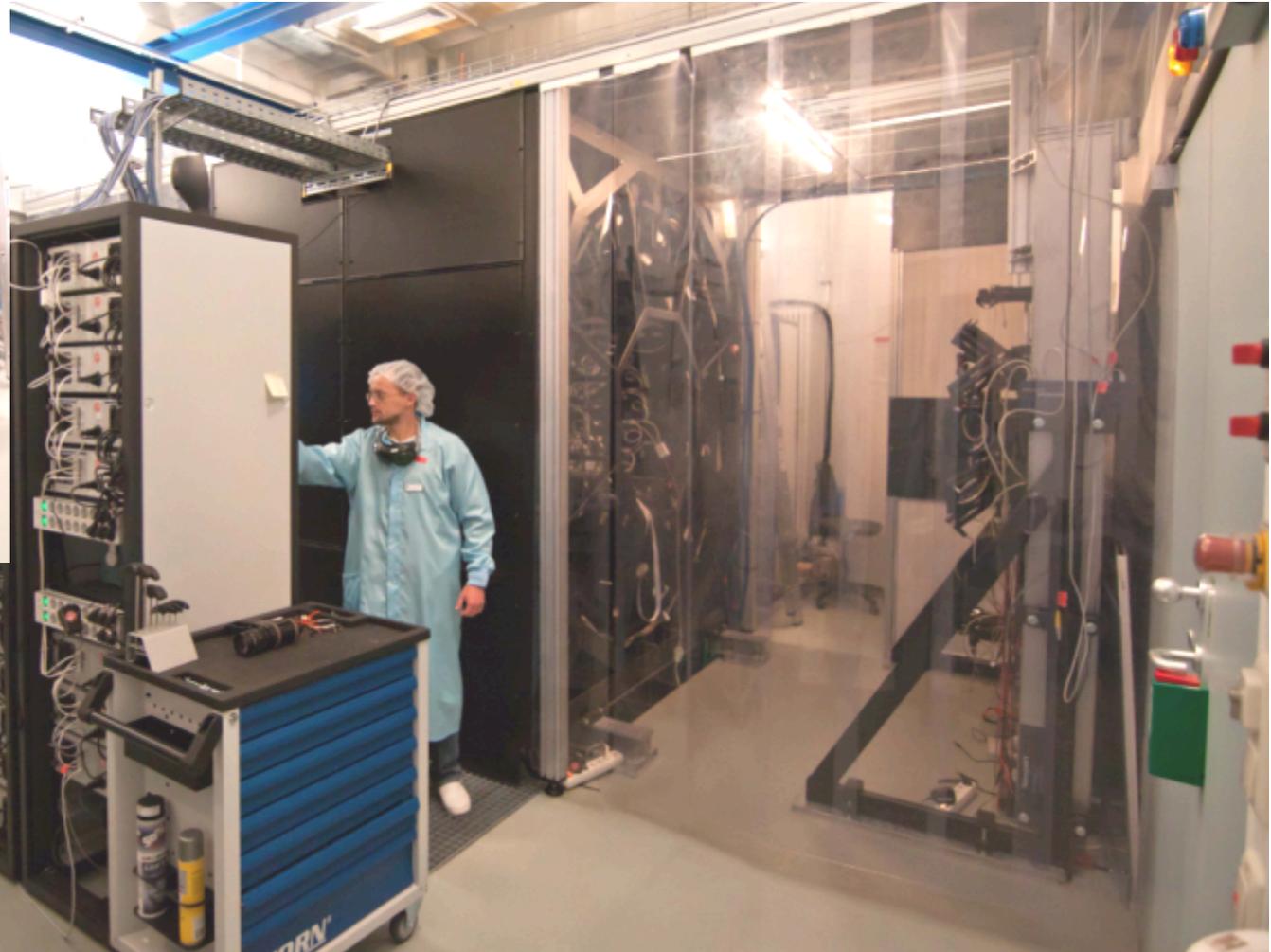
# A5 Setup



Size: 6 m x 3 m x 3 m

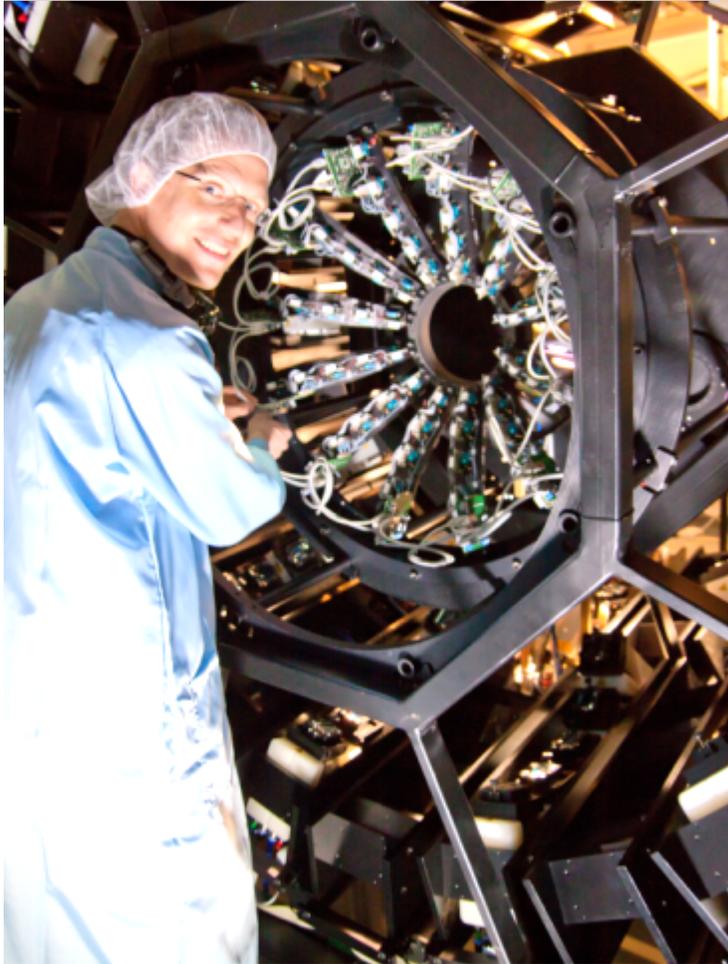
## A5 Photography

- Currently 120 laser diode stacks  $\lambda=940$  nm,  $P=2.5$  kW
- Upgrade to 240 stacks is possible
- $\text{Yb}^{3+}$  doped  $\text{CaF}_2$  crystal, or FP20-Glass with 35mm pump diameter



## A5 – two “detail” pictures...

Pump engine development  
with automatisisation finished.



Multi-pass amplifier setup:  
9 passes are currently installed

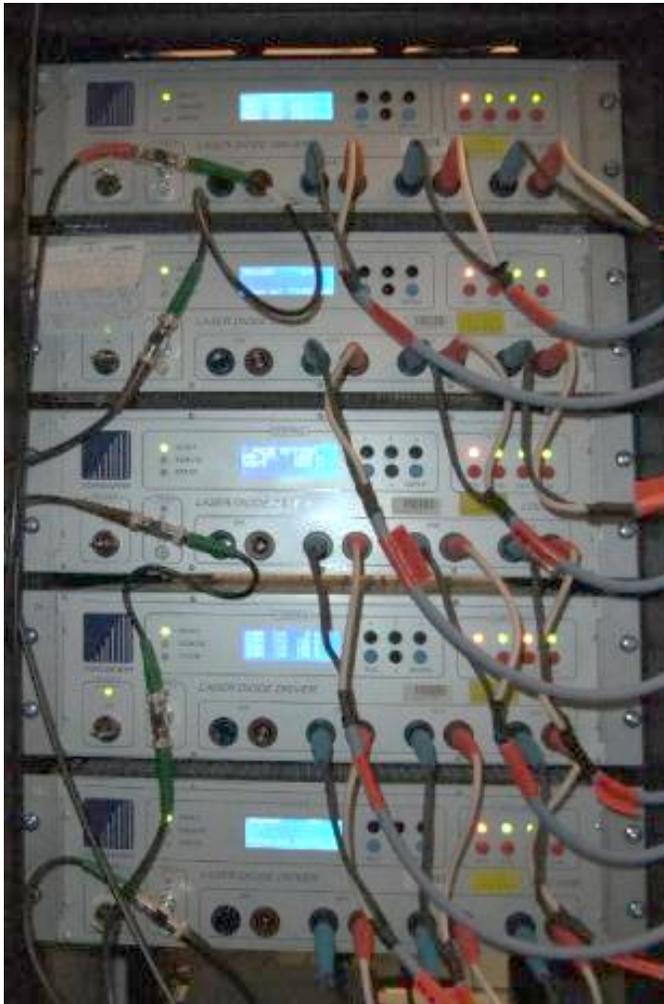


Beamline to the compressor will hopefully be finished within the next 2 month.

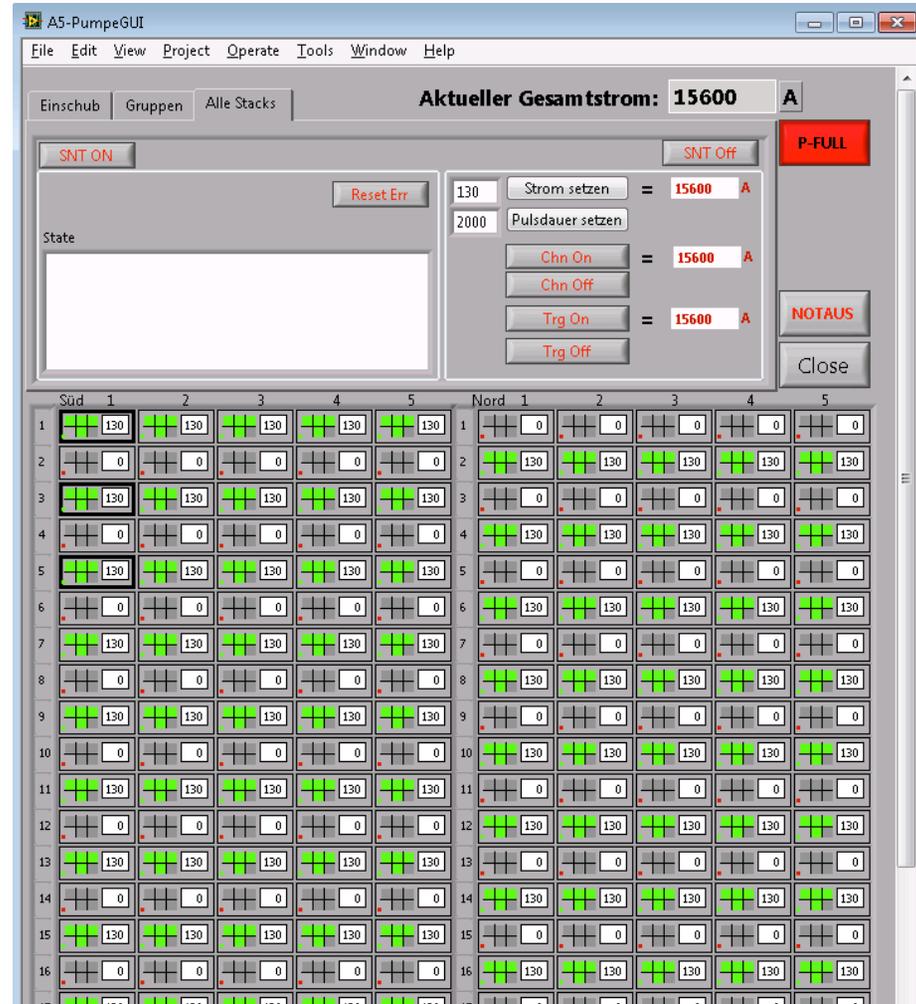
# Main Work Topics

## Control of 40 laser diode drivers:

Hardware:



Software:



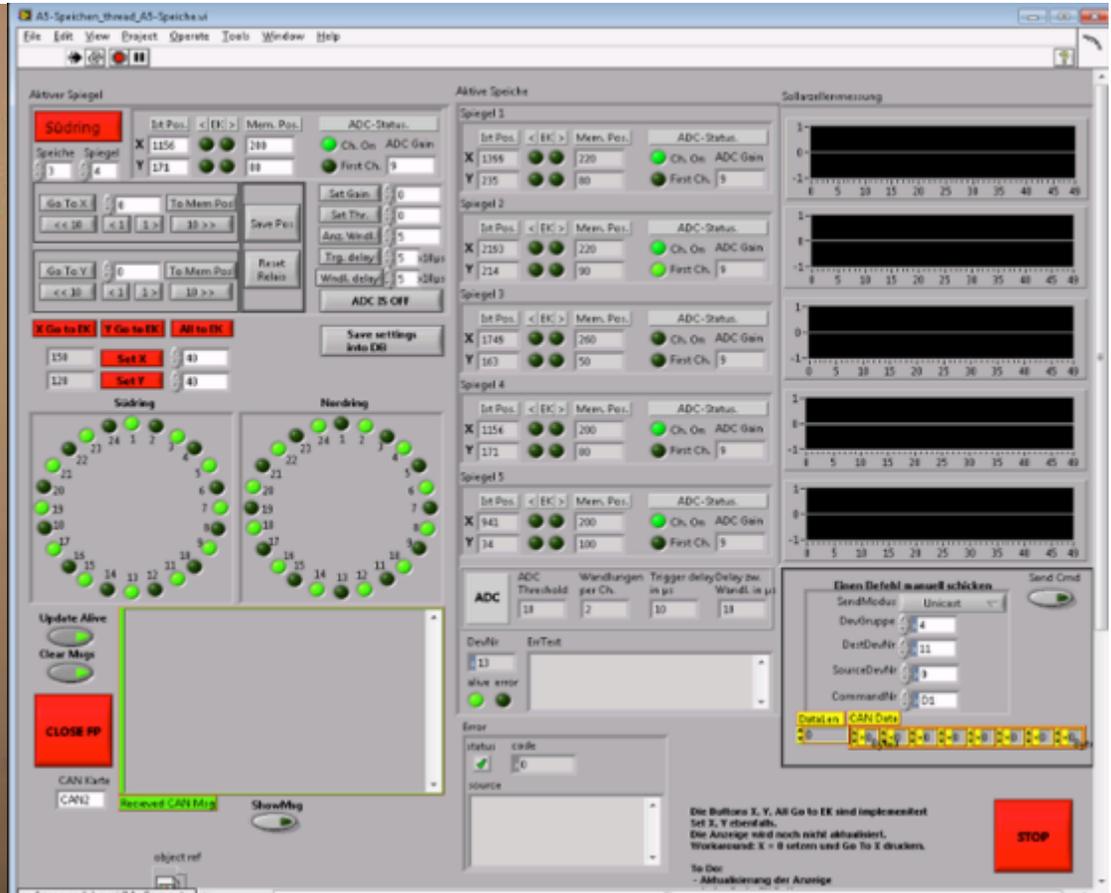
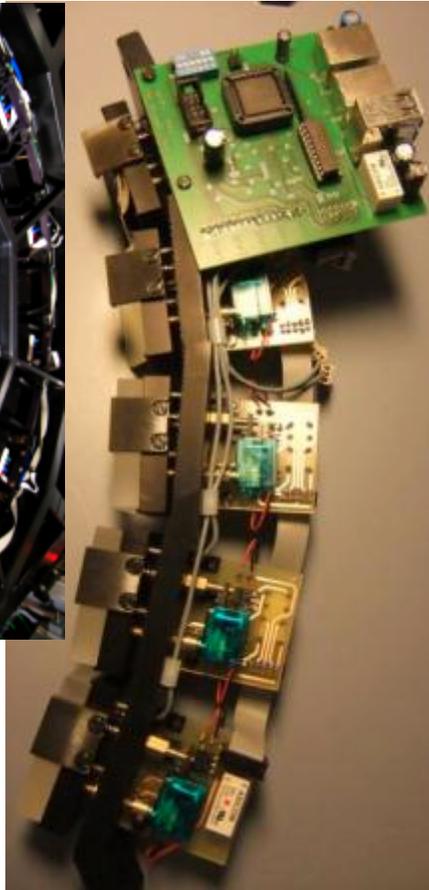
# Main Work Topics



## Pump spot alignment:

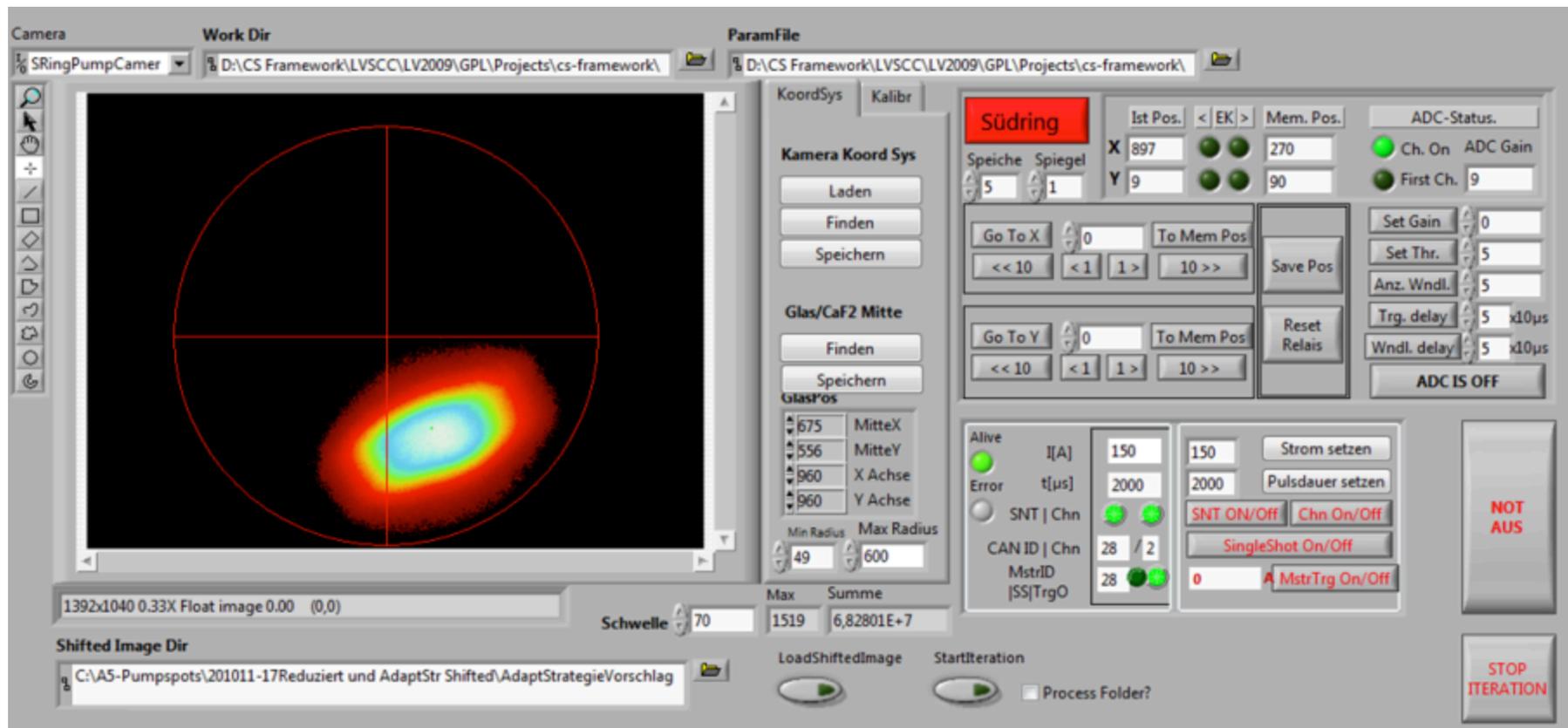
Hardware:

Software:



# Main Work Topics

## Recording and calibration of the pump spots:



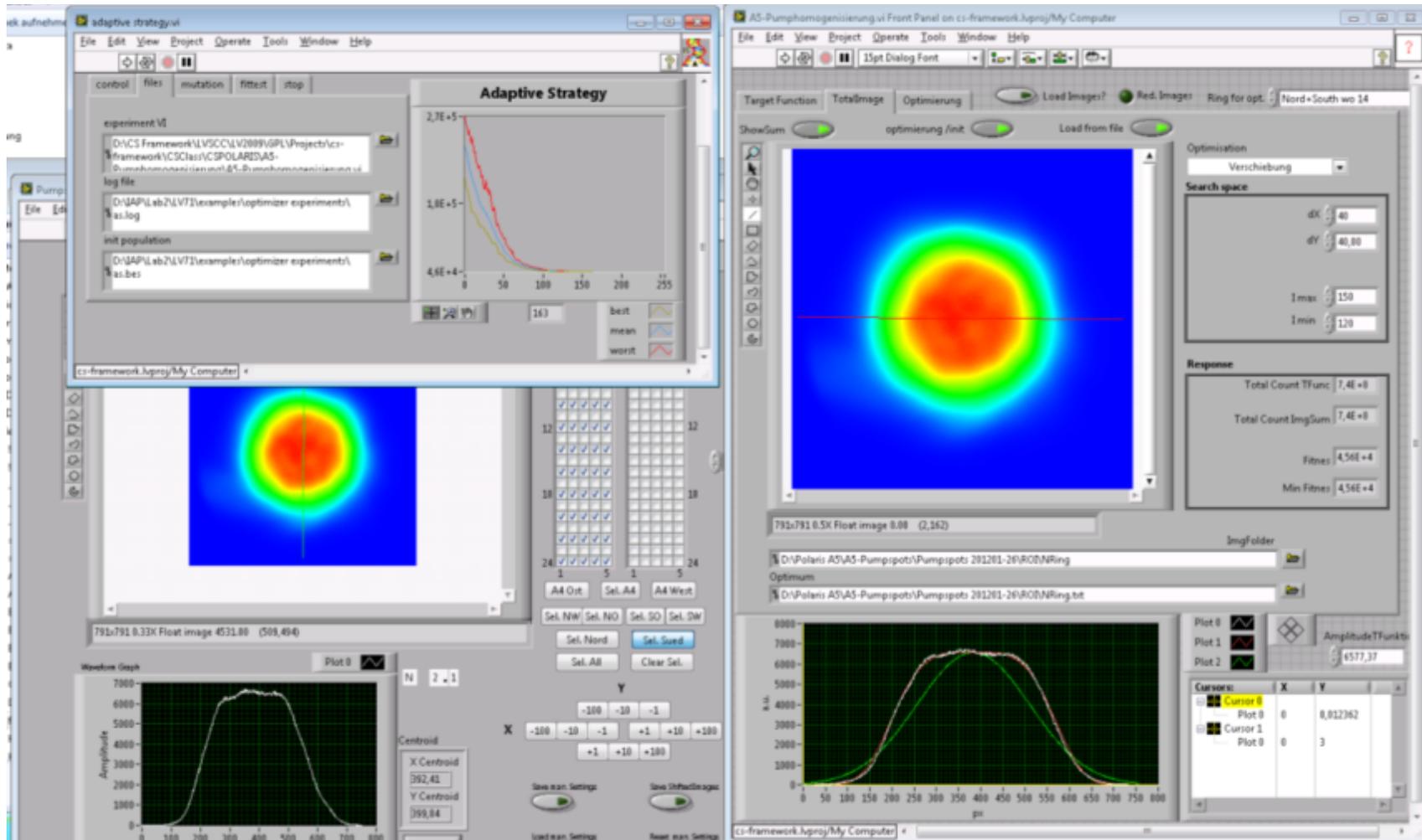
The screenshot shows a software interface for camera calibration and pump spot recording. The main window displays a camera view with a heatmap of a pump spot. The interface is divided into several sections:

- Camera View:** Shows a heatmap of a pump spot within a circular field of view. The spot is centered in the lower-right quadrant.
- Work Dir:** Shows the current working directory: `D:\CS Framework\LVSCC\LV2009\GPL\Projects\cs-framework\`.
- ParamFile:** Shows the parameter file path: `D:\CS Framework\LVSCC\LV2009\GPL\Projects\cs-framework\`.
- Koordinatensystem (KoordSys):** Includes buttons for 'Laden', 'Finden', and 'Speichern'.
- Glas/CaF2 Mitte:** Includes buttons for 'Finden' and 'Speichern'.
- GlasPos:** Lists coordinates: MitteX (675), MitteY (556), X Achse (960), Y Achse (960). Includes 'Min Radius' (49) and 'Max Radius' (600) fields.
- Positioning:** 'Ist Pos.' (X: 897, Y: 9) and 'Mem. Pos.' (X: 270, Y: 90) fields. Includes 'Go To X', 'Go To Y', and 'To Mem Pos' buttons.
- ADC-Status:** Includes 'Ch. On', 'ADC Gain', and 'First Ch.' (9) fields.
- Control Panel:** Includes 'Set Gain', 'Set Thr.', 'Anz. Wndl.', 'Trg. delay', and 'Wndl. delay' fields.
- Power and Pulse Settings:** Includes 'Alive', 'Error', 'SNT | Chn', 'CAN ID | Chn', 'MstrID', and 'SS|TrgO' fields. Includes 'Strom setzen', 'Pulsdauer setzen', 'SNT ON/Off', 'Chn On/Off', 'SingleShot On/Off', and 'MstrTrg On/Off' buttons.
- Status Area:** Includes 'NOT AUS' and 'STOP ITERATION' buttons.

# Main Work Topics



## Profile homogenization with genetic algorithm:

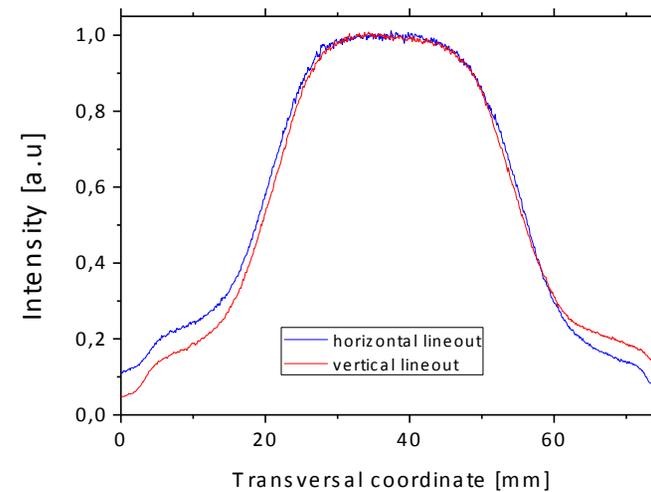
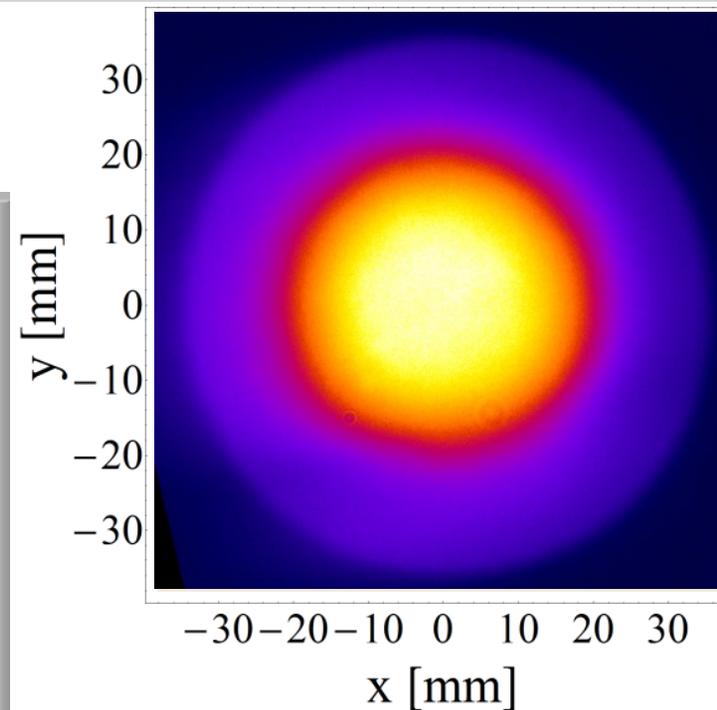
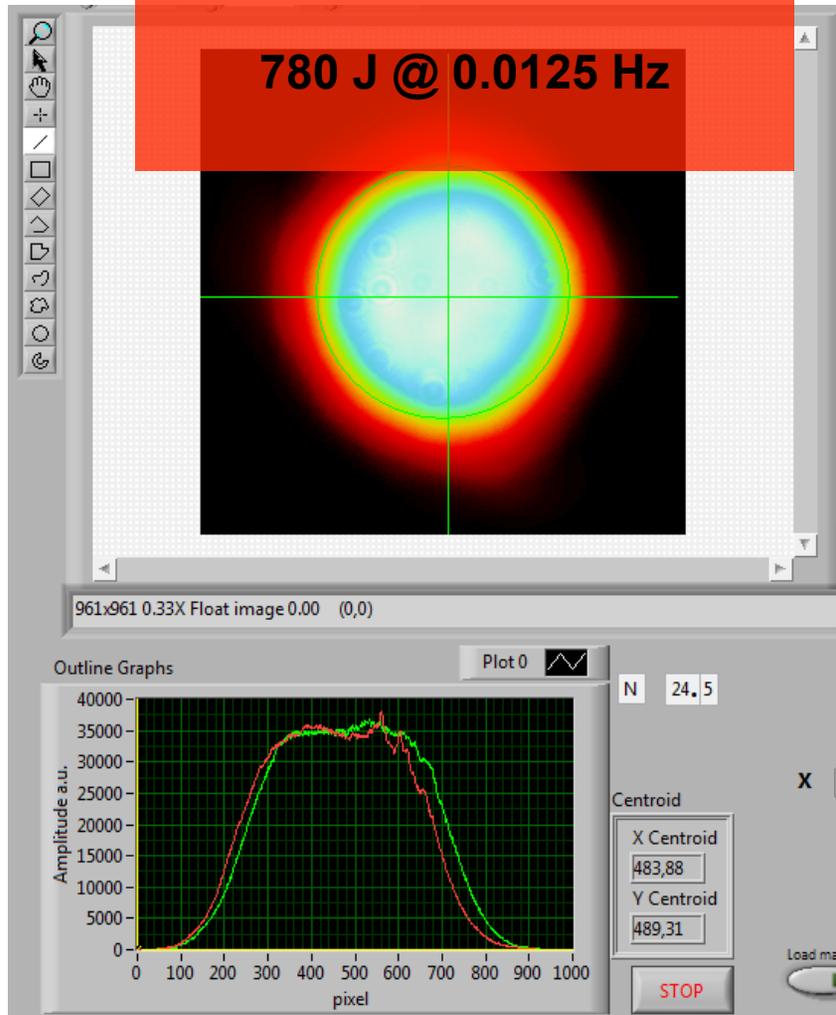


# A5 Pump Profile

Calculated pump profile with  
120 pump diode stacks

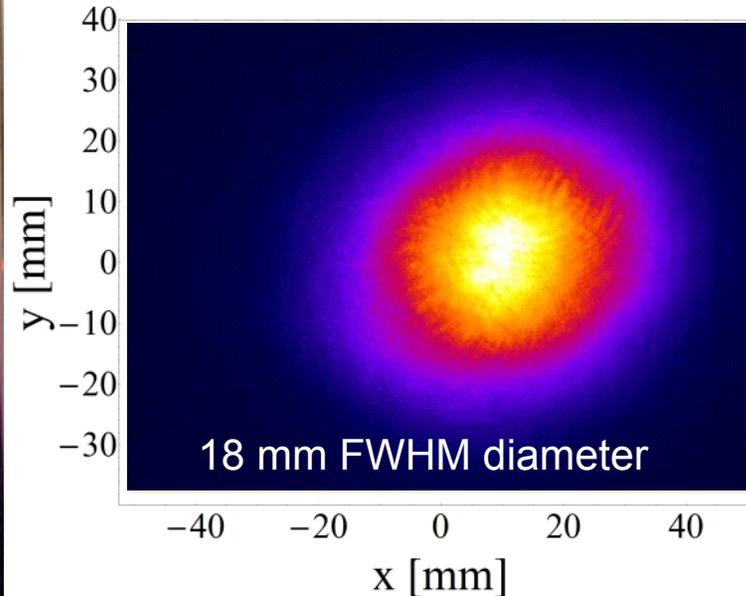
Measured pump profile:

**780 J @ 0.0125 Hz**

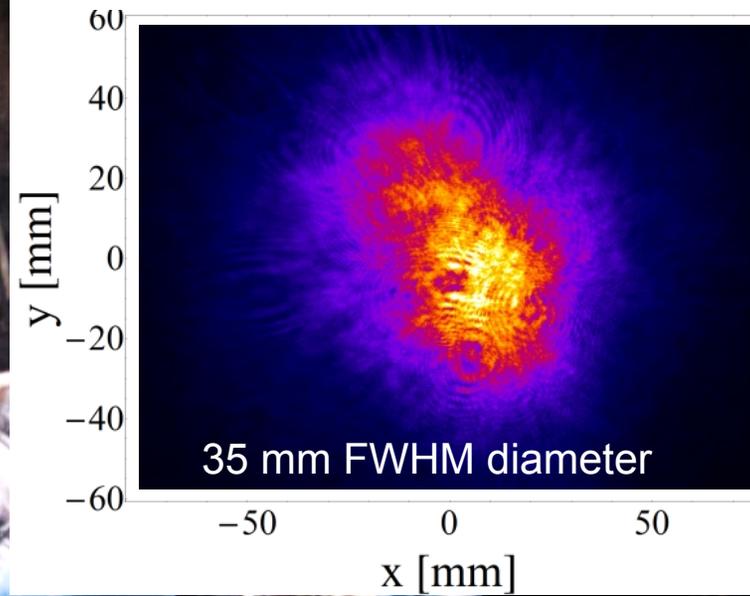


# Low Energy Amplification

Seed-Pulse:



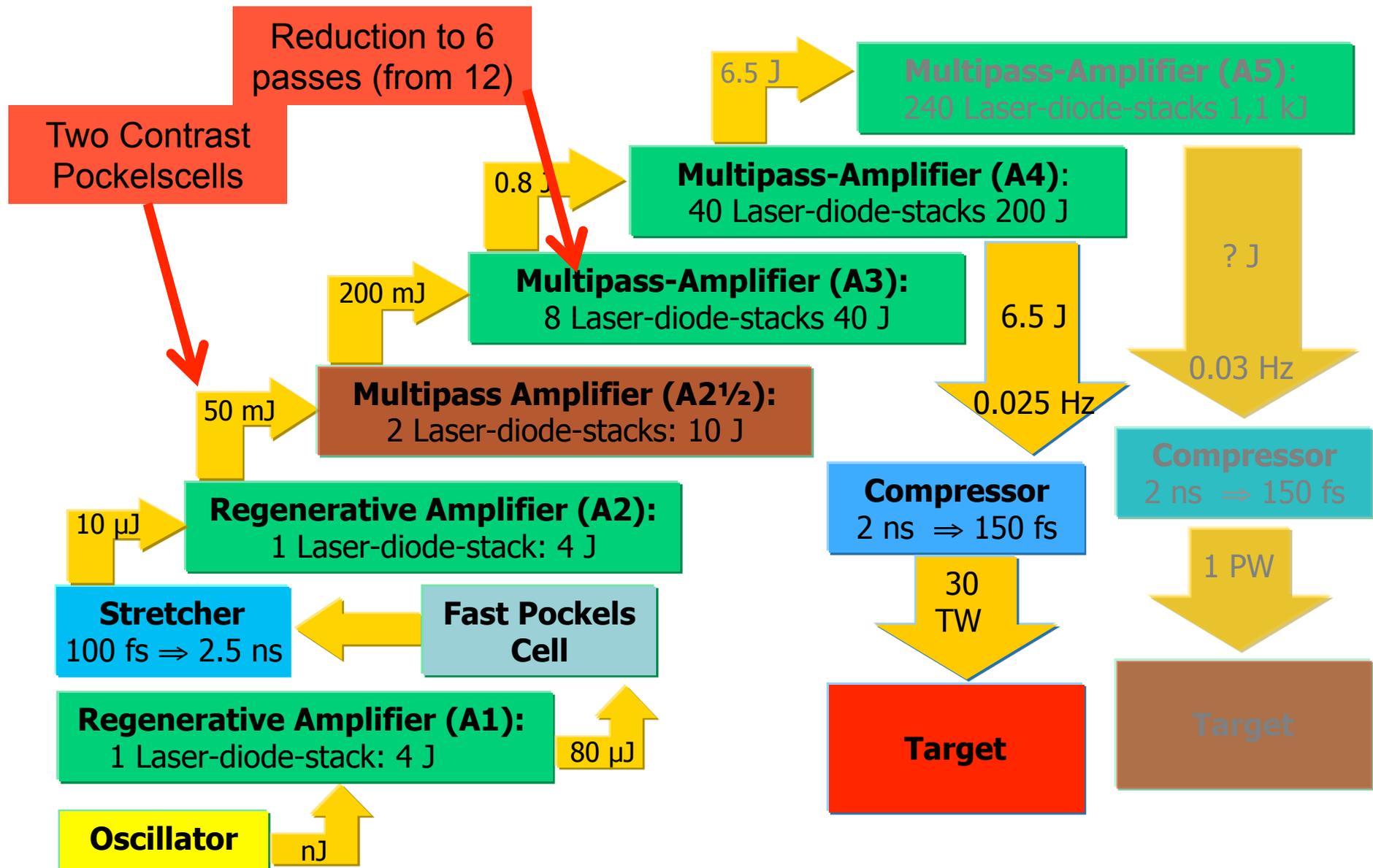
Amplified pulse:



- In 7-pass configuration a pulse energy of 40 mJ was achieved
- currently 9 passes are installed
- Gain = 3.2
- Active material: two 9 mm thick, 69 mm diameter, Yb:CaF<sub>2</sub>-disks
- Repetition-rate = 1/80 Hz

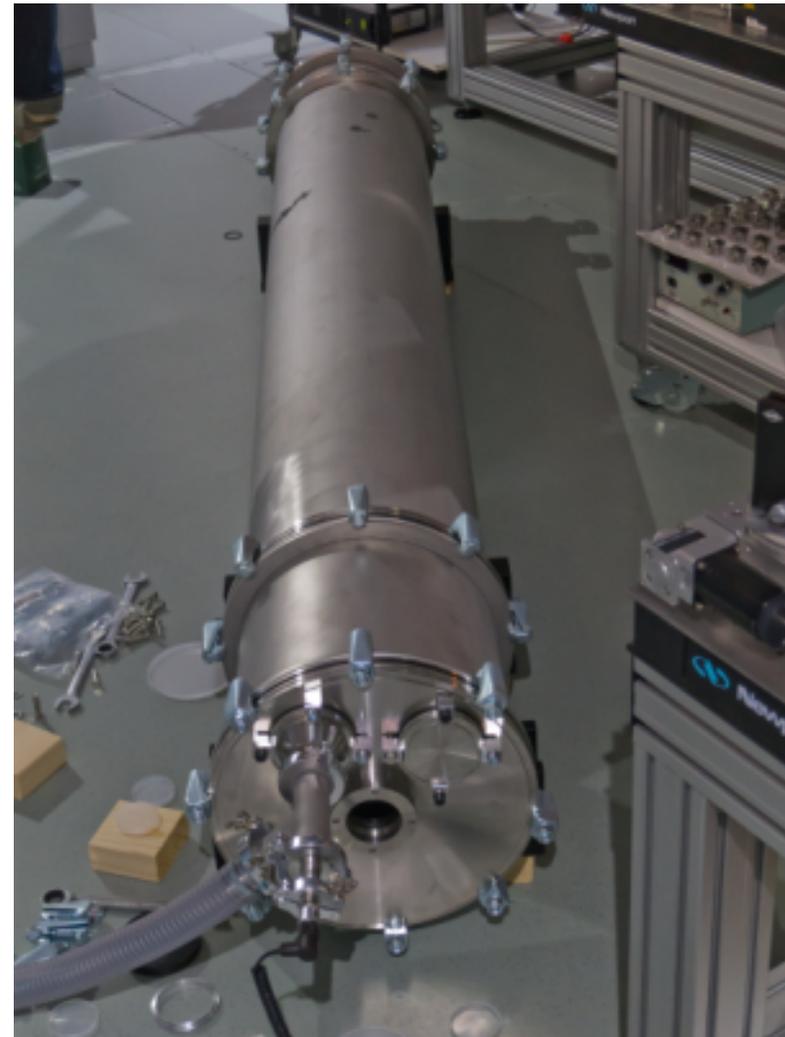
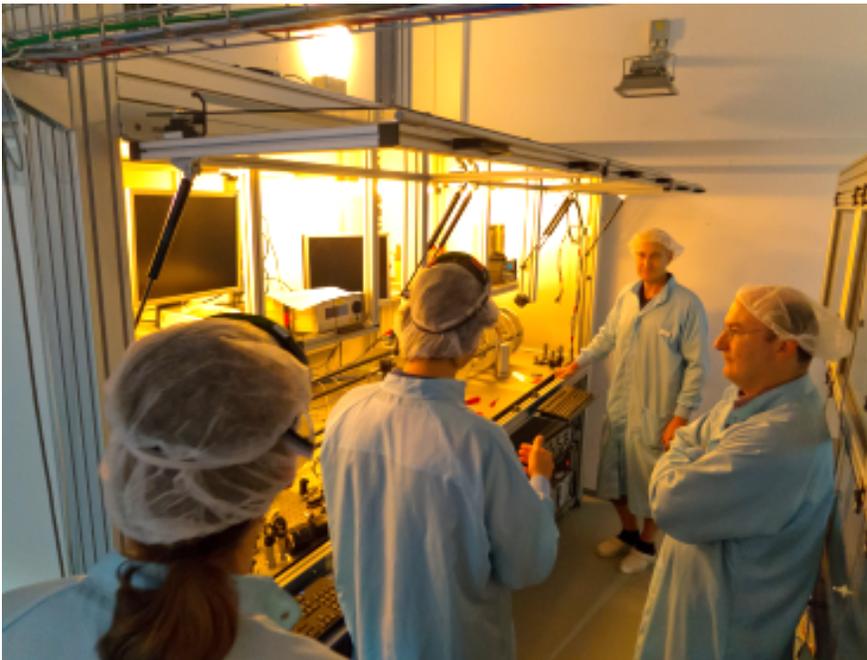
- Introduction
- Optimizing the peak intensity
- Optimizing temporal intensity contrast
- Operation and Stability
- Amplifier Development
  - A5
  - **Rebuild of A3**
  - Cryo burst laser system
  - A4 pump engine extension
- Conclusion

# Problem: Temporal Contrast “eats” Energy



## Rebuild of the “A3”

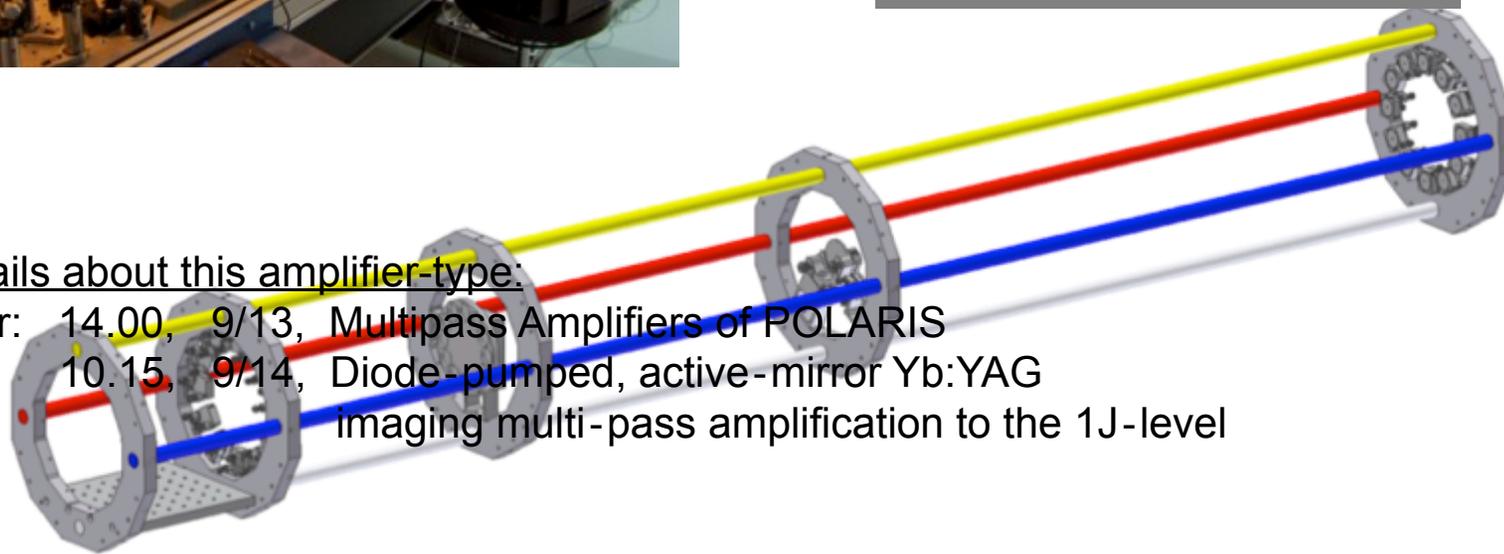
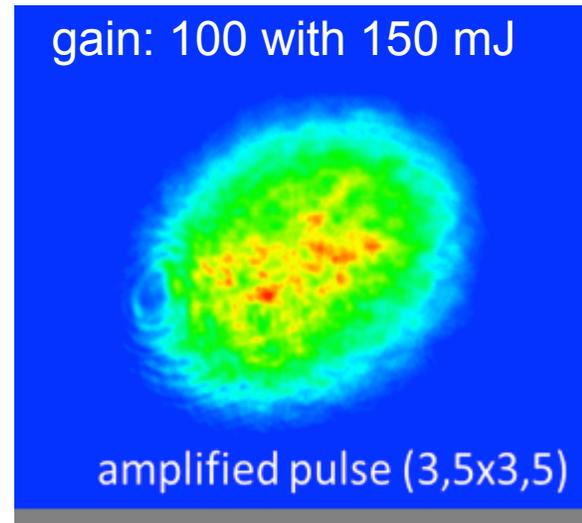
- A2.5 & A3 should be replaced
- A4 pulse energy is limited by the seed
- 20 passes with relay imaging
- 1.5 J pulse energy
- vacuum: stability improvement



# Outlook: Rebuild of A3



Output beam profile:



More Details about this amplifier-type:

S. Keppler: 14.00, 9/13, Multipass Amplifiers of POLARIS

C. Wandt: 10.15, 9/14, Diode-pumped, active-mirror Yb:YAG

imaging multi-pass amplification to the 1J-level

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# Cryo burst mode laser system

Up to 500 bursts of **500 pulses / 1 Mhz / 5J / burst**  
Reprate **10 Hz / Supporting pulse-lengths < 200 fs**

Active material: Yb:CaF<sub>2</sub>. Three amplifier stages, last two cryo cooled

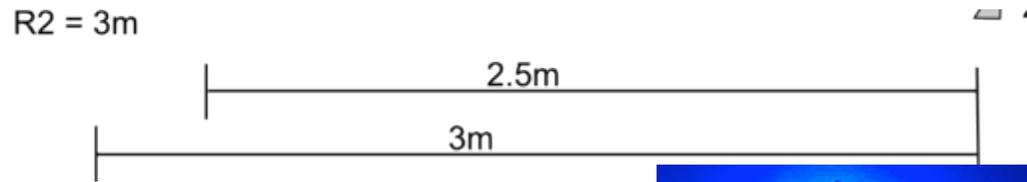
Optical setup: multipass relay imaging



Cryo Head:

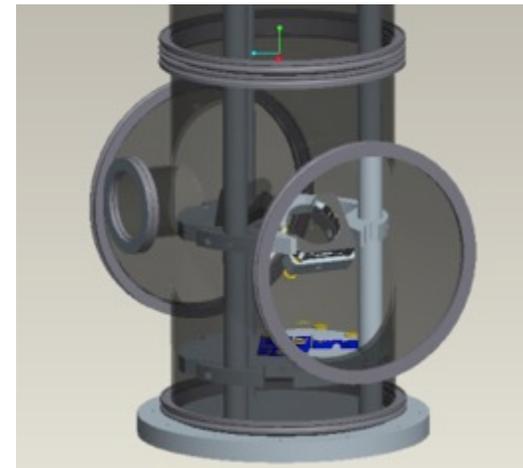
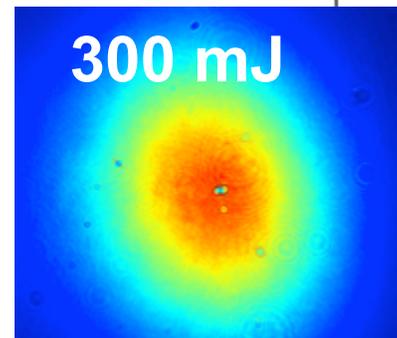


More details in J. Körners talk:  
9/14/2012 at 8.30



All amplifiers are on the table:  
2<sup>nd</sup> amplifiers stage has run  
first tests and achieved:

- Gain approx. 2000
- **300mJ**,
- **4.5nm FWHM** bandwidth

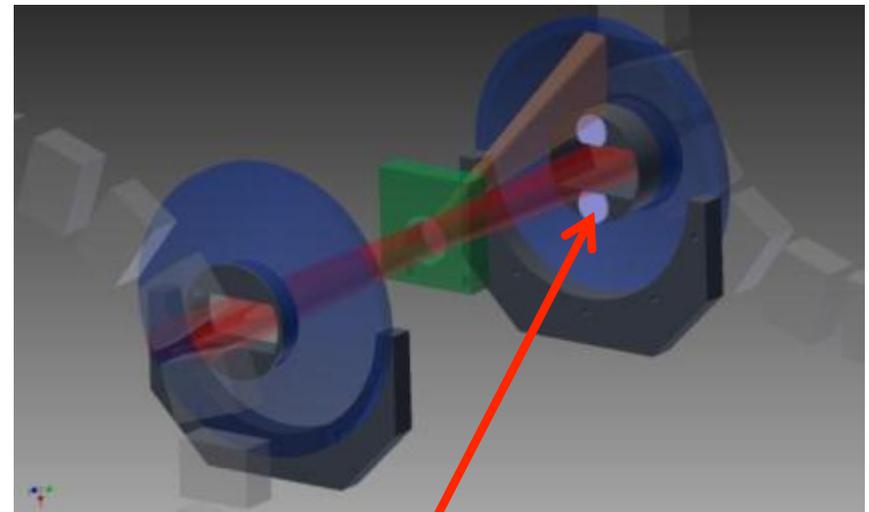
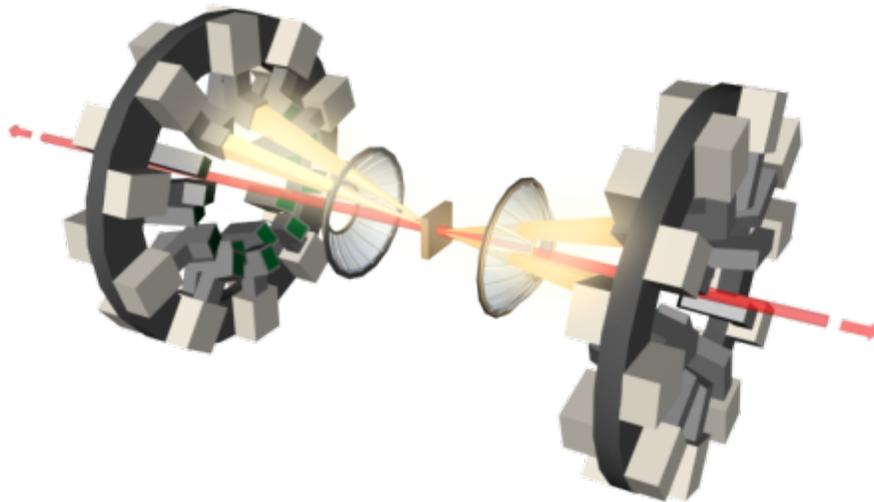


- Introduction
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# Outlook: A4 Pump-Engine Upgrade

## Motivation:

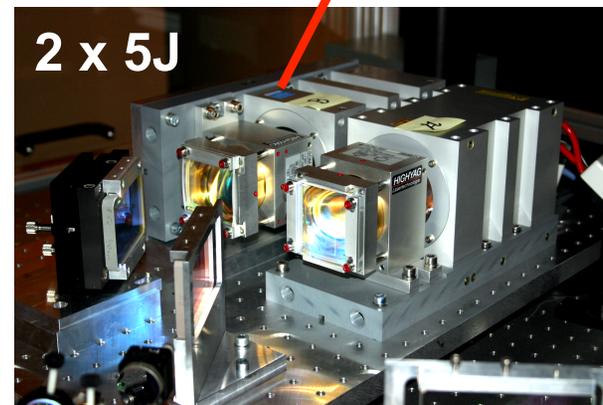
- number of pump spots (40) limits the pump profile homogeneity and size
- Pulse energy, near-field (beam) diameter is limited



Idea: 40J-A3 pump source as A4-extension !

- 8 stacks a 5 J
- 40 J pump energy
- Polarisation coupled

4 x



- **Milestone:** first experimental campaign with 1500 high-energy shots
- POLARIS is used for science 😊 (more than 7000 recorded interaction shots)
  - ....parallel development is going on (A5, new A3, Cryo, DCPA,...)
- Fully diode-pumped laser system:
  - $5 \times 10^{20}$  W/cm<sup>2</sup> peak intensity (adaptive optics, angular chirp compensation)
  - 6.5 J before compressor (4 J after compression)
  - 164 fs
- Temporal Contrast:  $10^{-9}$  for ASE and  $10^{-7}$  for (some residual) pre-pulses.
- A5 in final commissioning phase: first successful amplification tests
  - gain of 3.2 measured with 7-pass amplification

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Thank You!

A solid grey horizontal bar spans the width of the slide near the bottom.